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14. ABSTRACT
This report covers progress made in the development of a model to predict both injury and performance during basic training. Previously, we developed a preliminary model that predicted the stress fracture rate and used biomechanical modeling, nonlinear optimization for muscle force, and bone structural analysis to estimate bone stresses and strains from kinematic and ground reaction force measures. We broaden the work to address not only the overuse injuries, but the performance enhancement and metabolic demands associated with training. The novel performance component of the model relates the amount and intensity of training to its outcome by dosage-response relationships that can account for the enhancement in physical strength, the improvement of performance due to learning or acquaintance to the activities, and fatigue effects. In addition, training activities were quantified in order to determine model input parameters. In this report we also describe a software conceptual design that comes with an intuitive interface, demonstrating the application of the model in realistic situations.

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Executive Summary

In the previous phases of the overuse injury assessment project, we developed a preliminary model that predicted the stress fracture rate based on available field data. We also combined biomechanical modeling, inverse dynamics analysis, nonlinear optimization for muscle force, and bone structural analysis to estimate bone stresses and strains from kinematic and ground reaction force measures.

Since the goal of military training is efficient improvement the trainees' physical performance while minimizing possible injuries, we broaden the work in this phase of the research project to address not only the overuse injuries, but the performance enhancement and metabolic demands associated with training. We developed a research framework that has both injury and performance components and can potentially unify much of the research work in this broad and multi-disciplinary area. The injury (stress fracture) component recognizes the inherent variation of the bone damage and remodeling process by treating bone strain, which is the key variable to both the fatigue and repair of bone material, as a random variable. Using a mathematical representation of the distribution of the bone strain, complex factors such as difficulty of activities, physical status of the trainee, fatigue effects, and individual risk factors can be accounted for. The performance component relates the amount and intensity of training to its outcome by dosage-response relationships that can account for the enhancement in physical strength, the improvement of performance due to learning or acquaintance to the activities, and fatigue effects. Based on known performance energetic concepts, we adopted anaerobic work as a subjective dosage measurement that can be related to different activities. A metabolic demand component is also included in the modeling framework.

The framework was implemented as the Training, Overuse, and Performance (TOP) models. For demonstration purposes, simulations were conducted based on realistic training, injury, and performance data. The simulations simultaneously predicted the enhancement of performance due to training as well as the progression of damage in bone. The potential of bone stress fracture was a function of initial fitness level, the amount of training, and individual risk factor level.

We also developed a TOP software conceptual design that comes with an intuitive interface, demonstrating the application of the TOP model in realistic situations. A significant amount of effort was also spent in quantifying training activities in order to determine model input parameters.

Future work includes broadening the model framework to include addition ongoing research, validation of various model components by biomechanical testing and analysis, and implementation of the application software.

Table of Contents

1. Introduction

The U.S. military is a volunteer force and thus, places a premium on efficiently preparing the limited number of recruits for combat. The initial mechanism for this is basic training. However, a significant number of recruits are injured, resulting lost training days and reducing the number of available soldiers. Thus, there is a need to optimally increase physical readiness while reducing injury during basic training.

Our previous work in this area has focused on injury where we developed a preliminary model that predicts the stress fracture rate based on available field data (Sih et al. 2003; Woodmansee et al. 2004). We also combined biomechanical modeling, inverse dynamics analysis, nonlinear optimization for muscle force, and bone structural analysis to estimate bone stresses and strains from kinematic and ground reaction force measures.

Since the goal of military training is efficient improvement the trainees' physical performance while minimizing possible injuries, we broaden the work in this phase of the research project to address not only the overuse injuries, but the performance enhancement and metabolic demands associated with the training. This document describes our progress in these areas.

We begin by presenting a research framework that has both injury and performance components and can potentially unify much of the research work in these broad and multi-disciplinary areas. The framework was implemented as the Training, Overuse, and Performance (TOP) models. The advantage of this more complete framework is that it can serve as a tool to simultaneously optimize both performance and injury objectives. To this end we also present a TOP software conceptual design that comes with an easy to use interface, allowing the application of TOP models in realistic situations.

A significant amount of effort was also spent in quantifying training activities in order to determine model input parameters. Previously, training quantification focused on marching and running (Sih et al. 2003; Woodmansee et al. 2004). In this document, we summarize our effort to expand training quantification to other exercises.

2. Model Development

2.1 Model Framework

It is well established that training is needed to increase performance, but overtraining is detrimental and can cause injury (Figure 1). In previous work, our focus was to develop a biomechanically-based model to predict stress fractures during military basic training. While this document describes our work in this area, we also introduce additional models to address performance and metabolic cost issues. By modeling both the performance and injury aspects of training, users of the model will be in a better position to understand the implications of regiment changes and be able to reach performance goals while minimizing injury.

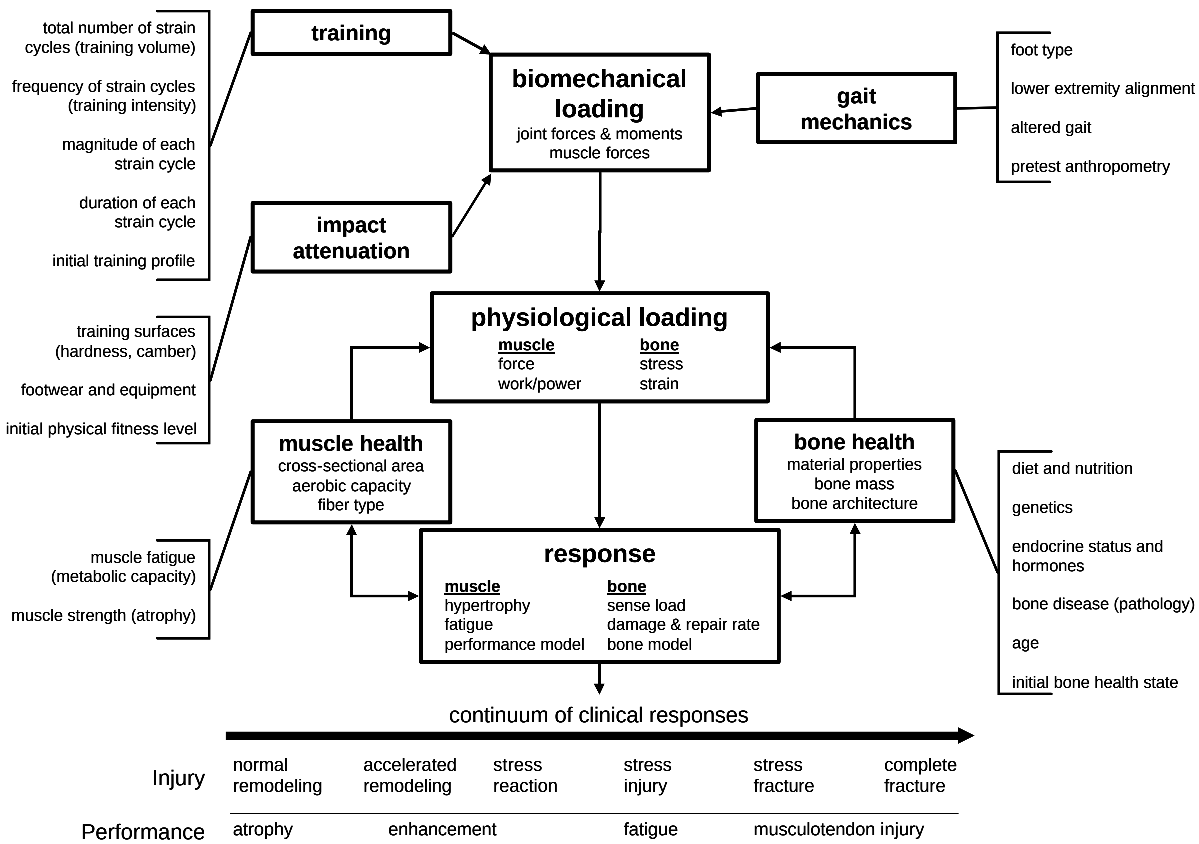

Figure 1. Theoretical pathway for both stress fracture injury and performance enhancement. Both pathways are dependent on biomechanical loading. Diagram based on the pathway suggested by the Subcommittee on Body Composition Nutrition and Health of Military Women (1998).

The nature of a model that incorporates both injury and performance is complex and multi-disciplinary and there is a lack of high quality data. To increase the chances of success, we design the model to be modular, allowing improvements to be added incrementally. We also focus on the end user, trying to use model input and outputs that are easy to understand while providing useful information. Where possible, a biomechanically-based model was chosen because a mechanical analysis naturally suggests future research areas and should have better predictive capability under varying conditions than an empirically-based model. See Figure 2. Thus, the objective of the Training, Overuse, & Performance (TOP) Models are:

- A theoretical framework that unifies overuse injury and performance research
- A modeling framework for future research and integrate existing isolated biomechanical research
- A preliminary set of models to test assumptions

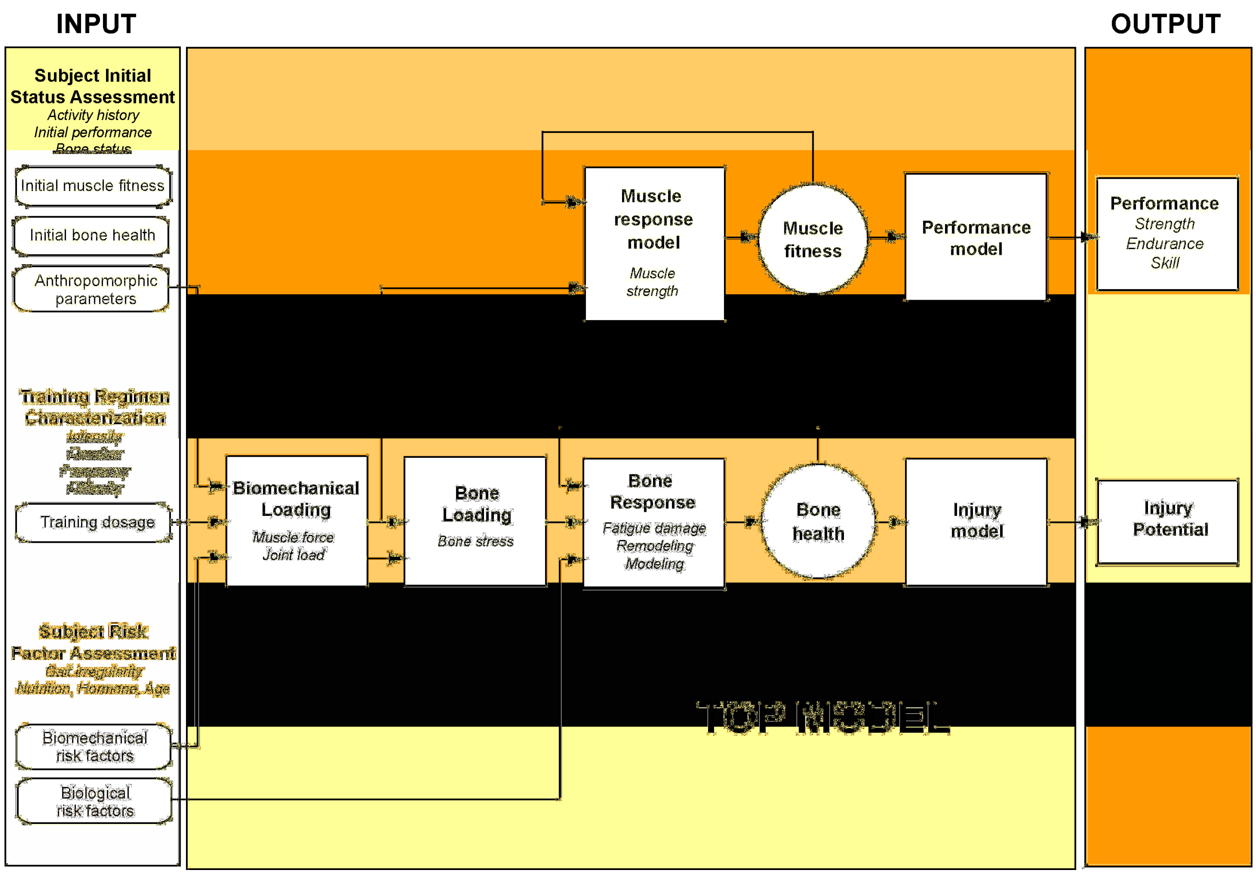

Figure 2. Overview of the general sub-components of the TOP model. Most users would only be concerned with the input and output modules.

2.1.1 Hypotheses

#1: Inherent variation of biomechanical activities

We assume/recognize that any biomechanical activity has its inherent variation that is beyond control. It can be measured or determined experimentally; but cannot be modeled as a deterministic process.

#2: Individual variation can be accounted for

There is individual variation of biomechanical activities. However, this can be determined from the inherently random process, if individual factors can be accounted for. This includes individual differences in known risk factors, physical performance capacity, and fatigue level.

2.2 Model Components

There are three components to the TOP model: Overuse Injury, Performance, and Metabolic Cost. This section describes each component in more detail, including equation derivations. The injury (stress fracture) component recognizes the inherent variation of the bone damage and remodeling process by treating bone strain, which is the key variable to both the fatigue and repair of bone material, as a random variable. Using a mathematical representation of the distribution of the bone strain, complex factors such as difficulty of activities, physical status of the trainee, fatigue effects, and individual risk factors can be accounted for. The performance component relates the amount and intensity of training to its outcome by dosage-response relationships that can account for the enhancement in physical strength, the improvement of performance due to learning or acquaintance to the activities, and the fatigue effects. Based on known performance energetic concepts, we adopted anaerobic work as a subjective dosage measurement that can be related to different activities. A metabolic demand component is also included in the modeling framework.

2.2.1 Overuse Injury (Bone) Model

Literature Review

An extensive literature review of different stress fracture models, including the advantages and disadvantages, was conducted in a previous report (Woodmansee et al. 2004).

TOP Bone Model

The TOP Bone component is based primarily on the Martin model (2001), where a small amount of damage occurs with each cycle (step) and begins to accumulate. This is offset by a repair process. Additional details on this model can be found in our previous report (Sih et al. 2003). We also introduce distributions, which modify the Martin model response by changing the bone strain. This allows the model to account for individual and inherent variability as well as biomechanical and biological risk factors.

Bone strain of a given activity

The primary input to the TOP Bone Model is bone strain. To account for the inherent variation in bone strain during various activities, we estimate an "ideal" strain and impose variability by multiplying the strain by different statistical distributions.

If we assume bending is the primary loading condition, for a given individual and activity bone strain *e* is calculated using a typical bending strain equation:

$$e = \frac{c \cdot \mathrm{M}}{\mathrm{E}_0 \mathrm{R}^3 \left(1\text{-}p\right)^3} \qquad 1$$

where *c* is an activity-dependent coefficient (marching, running, etc.) that converts bending moment M to the strain due to the biomechanical loading at the bone level. E_0 is maximum elastic modulus, *p* is bone porosity and R is cross-sectional radius of the bone. Thus, the equation for strain is influenced by loading, geometry, and material properties. To account for inherent variation and individual variation, Equation 1 can be rewritten as

$$e = \frac{c \cdot \mathrm{M}}{\mathrm{E}_0 \mathrm{R}_0^3} \cdot \frac{1}{\left(1+\Delta\mathrm{R}\right)^3} \cdot \frac{1}{\left(1-p\right)^3} \qquad 2$$

where the first term represents an individual's maximum strain and the remaining terms contain variables that are adjusted to reflect the inherent variation of bone strain. Thus, if we let e^* represent the first term and S_{diff} represent the inherent variation distribution generated by the remaining terms, then strain for a given individual is:

$$e = e^* \cdot S_{\mathrm{diff}} \qquad 3$$

To account for individual variation due to risk factors, performance level and fatigue, additional distributions can be used to modify Equation 3:

$$e = e^* \cdot S_{\mathrm{diff}} \cdot S_{\mathrm{risk}} \cdot S_{\mathrm{perf}} \cdot S_{\mathrm{fatigue}} \qquad 4$$

An ideal maximum strain e^* is obtained by determining *c*, E_0, R_0, and M in the laboratory analyzing subjects conducting a given activity under normal conditions. S_{diff}, the inherent variation, is a function of terrain, environment, and other external factors. S_{risk} represents the variation due to different biomechanical risk factors and is a function of anthropometry, gait pattern, and other identified risk factors of the individual. S_{perf} varies strains depending on athletic state and S_{fatigue} reflects changes due to short term (minutes to hours) fatigue.

Converting known measures to different S variations will depend on the measurement. We envision a function which converts a known variable into variation S (Figure 3). Derivation of the function will require a thorough biomechanical analysis and / or risk factor analysis.

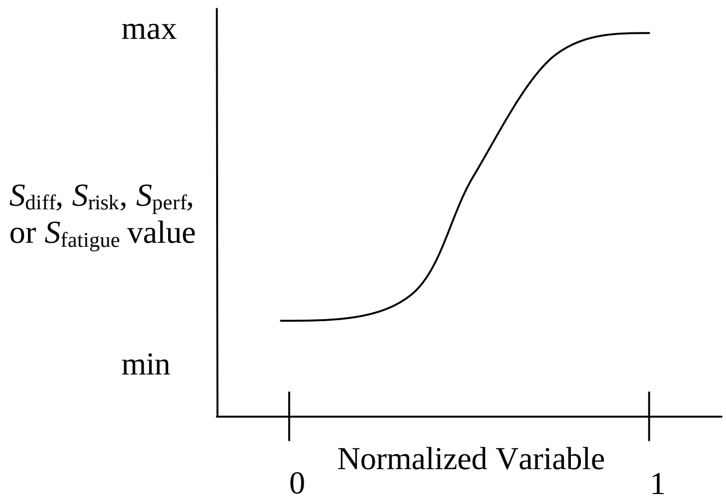

Figure 3. Theoretical graph depicting how different variations can be determined from measured variables. Shape of graph would be determined experimentally or through literature reviews and is a function of external factors such as terrain, environment and equipment. This method would allow the quantification of inherent bone strain variation (S_{diff}), risk factors (S_{risk}), performance capabilities (S_{perf}), and fatigue (S_{fatigue}).

In summary, Equation 4 is used to create a bone strain distribution based on Hypothesis #1 and #2 (see page 4). This formulation assumes that (1) bone strain is independent of initial bone geometry, (2) bone strain is dependent on bone material quality, and (3) the primary loading condition is bending.

Bone damage model

Using the model based on Martin (2001), we assume that daily fatigue damage change is the summation of all steps

$$\dot{D}_F = \sum_{\mathrm{day}} k_D e^{q} \qquad 5$$

where strain e is dependent on the parameters described in Equation 4, and k_D and q are damage coefficients.

Bone remodeling model

Again using the equations put forth by Martin (2001), damage repair is a function of the current damage level D and basic multicellular unit (BMU) parameters:

$$\dot{D}_R = D \cdot f_a \cdot p \cdot r_c^2 \cdot F_S \qquad (6)$$

where f_a is the BMU activation frequency, r_c is the BMU radius, and F_S is the likelihood of removing damage factor. The form of the equation describing BMU activation frequency is unknown but Martin (2001) suggests the sigmoidal-shaped function:

$$f_a = \frac{f_{a0} \cdot f_{a\max}}{f_{a0} + (f_{a\max} - f_{a0}) \exp\left[-k_R (D - D_0)/D_0\right]} \qquad (7)$$

Values and definitions for the parameters in Equation 7 can be found in Table 11.

Starting equilibrium damage level

Equating damage and remodeling equations during initial conditions gives the initial equilibrium damage:

$$D_0 = k_D \left(\sum_{\text{day}} e^{q} \right)_0 \Big/ \left(p \cdot r_c^2 \cdot f_{a0} \cdot F_S \right) \qquad (8)$$

Porosity and elastic modulus changes

Using estimates of BMU activity, Martin (2001) estimates porosity changes with the following equation:

$$\dot{p} = Q_B \int_{t-(T_R+T_I+T_F)}^{t-(T_R+T_I)} f_a dt - \left(1 - \frac{Q_B}{Q_C}\right) Q_C \int_{t-(T_R+T_I+T_F)}^{t-(T_R+T_I)} f_a dt \qquad (9)$$

Porosity is then related to elastic modulus using:

$$E = (1-p)^3 E_0 \qquad (10)$$

Values and definitions for the parameters in Equations 9 and 10 can be found in Table 11.

Periosteal modeling

Periosteal modeling (the addition of bone on the outer surface of bone) was estimated to be a function of damage (Martin 2001):

$$M_p = \begin{cases} k_p \left(D - D_0\right) / D_0 & D < D_C \\ M_w & D > D_C \end{cases} \qquad 11$$

where M_w is the rate for woven bone, which is created in high damage situations. To adjust the rate of modeling at lower damage levels, k_p is assumed to be related to M_w and damage:

$$k_p = \frac{M_w}{\left(D_C / D_0\right) - 1} \qquad 12$$

Thus, the change in bone radius $\dot{R}$ is M_p. Values and definitions for the parameters in Equation 12 can be found in Table 11.

Calculate daily damage accumulation

Referring to Equation 4, we note that $S_{fatigue}$ and S_{diff} are short-term variables. The remaining components do not need to be updated daily and, thus, can be considered a constant k:

$$e = k \cdot e^* \cdot S_{fatigue} \cdot S_{diff} \qquad 13$$

Since damage is related to strain through Equation 5, daily damage can now be written as:

$$D = \text{cnst} \cdot \sum \left(e_i^*\right)^q \cdot S_{fatigue_i}^q \cdot S_{diff_i}^q \qquad 14$$

where cnst incorporates k and k_D.

Parameters

In this section, we report on the important bone model parameter values acquired through a literature review.

In vivo Strain Measurements

In vivo strain measures are important because they are a direct measure of the loads felt by the bone during various exercises and can be directly compared to the strains estimated by the TOP model. Currently, strains are measured using surface gauges that surgically attached to the periosteal surface of different bones. While these measurements do not contain information about the internal strains, loading theory tells us that normally the highest strains (and stresses) occur on the outer surface of solids. Table 1 lists the average and standard deviations for bone strains measured *in vivo* at different locations of the tibia and 2^{nd} metatarsal for walking, running, and jumping.

Table 1. ***In vivo*** **strain summary table (Arndt et al. 2002; Burr et al. 1996; Carter and Hayes 1977; Ekenman et al. 1998; Ekenman et al. 2002; Fyhrie et al. 1996; Lanyon et al. 1975; Milgrom et al. 1996; Milgrom et al. 2000a; Milgrom et al. 2000b; Milgrom et al. 2001; Milgrom et al. 2002; Milgrom et al. 2003).**

		Compression		**Tension**		**Shear**		
Location	**Movement**	**Strain µe**	**Strain Rate µe/s**	**Strain µe**	**Strain Rate µe/s**	**Strain µe**	**Strain Rate µe/s**	**N # data pts**
2nd met-mid-dorsal	jump	3396±519		3748±641				3
2nd met-mid-dorsal	run	2536±174	25289±4636	731±118	9073±3232			4
2nd met-mid-dorsal	walk	2045±837	5170±1755	310±217	5597±1548			36
tibia-distal-medial	jump	1170		1277				3
tibia-distal-medial	run	547		1124				1
tibia-distal-medial	walk	1065		950				1
tibia-mid-anteromedial	run	387±25	12375	474±37				4
tibia-mid-anteromedial	walk	183±22	3120	190±27				24
tibia-mid-medial	jump	1745±692	12178±10549	1200±399	6188±4701	6453±4004	41066±21622	27
tibia-mid-medial	run	1312±635	11116±2059	1032±243	10829±1246	3623±2761	41684±23353	92
tibia-mid-medial	walk	615±151	4192±773	588±117	4691±579	1273±453	13633±4119	96

Note: Both mean and s.d. are weighted averages of reported means and s.d.'s, respectively. Unlabeled variation values assumed to be s.d. and not s.e.m. No distinction was made between individual and group reported data. N (# data pts) is the maximum number of data points available and may count the same subjects multiple times.

Bone Mineral Density

The definition of bone mineral density depends on the measurement method. For laboratory specimens, true density (gm/cm^3) is reported but varies depending on the preparation. Validation for the TOP model would benefit from an *in-vivo* estimate for a large number of subjects. DXA scans are currently used but estimate area density in gm/cm^2. Unfortunately, the relationship between area and true density has not been thoroughly investigated. Another promising noninvasive method is quantitative computed tomography (CT or qCT), which gives a 3D view of the bone and can estimate true density (gm/cm^3). However, few values have been reported in the literature. Lacking better data, we report the average and standard deviation for the more commonly reported DXA mineral density (Table 2).

Table 2. Average bone mineral density values reported in the literature (Beck et al. 1996; Beck et al. 2000; Behncke 1993; Crossley et al. 1999; Forwood and Parker 1989; Hutchinson et al. 1995; Lauder et al. 2000; Muller and Ruegsegger 1996; Nordstrom et al. 1998; Pettersson et al. 2000; Pouilles et al. 1989; Wachter et al. 2002).

Location	gm/cm^2	# data pts
foot-calcan	0.6±0.1	43
femur-distal	1.4±0.2	114
femur-mid	2.2±0.2	745
femur-neck	1.0±0.1	317
femur-prox (g/cm^3)	1.2±0.1	23
fibula-distal	1.3±0.2	610
spine-lumbar	1.2±0.1	282
tibia-distal	1.6±0.2	649
tibia-mid*	1.4±0.2	223
tibia-proximal	1.2±0.1	114

*g/cm^3 data point also available.
Note: Both mean and s.d. are weighted averages of reported means and s.d.'s, respectively.

Elastic Modulus

Elastic modulus E is a measure of a material's stiffness or ability to deform and often has the dimensions of N/m^2 or pascal (Pa). By definition, the elastic modulus is the slope of the linear portion of a stress-strain curve. Table 3 gives a partial review of the elastic modulus values for bone found in the literature. Because testing requires a precise measure of both load and distance, most bone values were not acquired from *in vivo* specimens.

Table 3. Elastic modulus literature review summary table.

Source	Bone Type	Species	Test Method	Elastic Modulus (GPa)	Notes
(Wolff 1892)[1]	trabecular		Hypothesis	17-20	assumed
(Runkle and Pugh 1975)[1]	trabecular	human	Buckling	8.69±3.17	dry
(Townsend et al. 1975)[1]	trabecular	human	Inelastic buckling	11.38	wet
(Williams and Lewis 1982)[1]	trabecular	human	Back-calculating from finite element models	1.30	
(Ashman and Rho 1988)[1]	trabecular	human	Ultrasound test method	13.0±1.47	wet
(Kuhn et al. 1989)[1]	trabecular	human	Three-point bending	3.81	wet
(Mente and Lewis 1989)[1]	trabecular	human	Cantilever bending w/ FEM analysis	7.8±5.4	dry
(Choi et al. 1990)[1]	trabecular	human	Four-point bending	5.35±1.36	wet
(Rho et al. 1993)[1]	trabecular	human	Tensile testing	10.4±3.5	dry
(Rho et al. 1993)[1]	trabecular	human	Ultrasound testing method	14.8±1.4	wet
(Rho et al. 1997)[1]	trabecular	human	Nanoindentation	19.6±3.5	dry, longitudinal dir
(Rho et al. 1997)[1]	trabecular	human	Nanoindentation	15.5±3.0	dry, transverse dir
(Rho 1996)	trabecular	human	Ultrasound test method	0.769±0.534	wet
(Ryan and Williams 1989)[1]	trabecular	bovine	Tensile testing	0.76±0.39	
(Hodgskinson et al. 1989)[1]	trabecular	bovine	Microhardness	15	estimation
(Kuhn et al. 1989)	cortical	human	Three-point bending	4.89	wet
(Rho et al. 1993)[1]	cortical	human	Tensile testing	18.6±3.5	dry
(Rho et al. 1993)[1]	cortical	human	Ultrasound testing method	20.7±1.9	wet
(Rho 1996)	cortical	human	Ultrasound test method	20.7±1.9	wet
(Wachter et al. 2002)	cortical	human	Compression test	1.76±0.72	wet

[1]Survey conducted in Jae-Young Rho, L. Kuhn-Spearing, and P. Zioupos. Mechanical properties and the hierarchical structure of bone. *Med.Eng.Phys.* 20 (2):92-102, 1998.

Bone Geometry

Bone geometry is needed to calculate the loading distribution on the bones. The following are summary values for the femur, tibia, and fibula length, cross-sectional area, diameter, and moment of inertia found in the literature.

Table 4. A summary of average bone geometry values found in the literature (Beck et al. 1996; Crossley et al. 1999; Milgrom et al. 1988; Milgrom et al. 1989; Milgrom et al. 1991; Piziali et al. 1980; Rittweger et al. 2000; Stein and Granik 1979; Stein et al. 1998).

Location	Length cm	Cross-Sect Area mm2	Diameter, mm A-P	Diameter, mm M-L	Moment of Inertia, mm4 A-P	Moment of Inertia, mm4 M-L	N # data pts
femur-distal	52.1±2.9	402			31516	29744	2
femur-mid		534±68		25±2	29582	27189±7218	612
femur-prox		545			30863	30291	2
fibula-distal		96±17		12±2	573	1063±480	612
fibula-mid		162			1148	943	2
fibula-prox		178			1191	1123	2
tibia-distal	40.2±2.4	359±48	24±2	24±2	17896±4856	16542±4851	1417
tibia-mid		300±40	26±2	26±2	18153±4623	26503±4948	301
tibia-proximal		428±38			35195±7688	21066±4633	93

Risk Factors

An extensive literature review indicates that there are no consistently identified risk factors for stress fractures (Woodmansee et al. 2004). However, in a review by Bennell et al. (1999), the authors suggest that bone cross-sectional area, initial fitness level, and menstrual status are likely the dominant risk factors for stress fractures in the military. The following tables list the risk values typically seen in the literature for bone cross-sectional area and initial fitness levels.

Table 5. Studies finding bone cross-sectional area is a significant risk factor for stress fractures.

			Stress Fracture			Normals			Statistic		
Source	Bone	Method	N	Ave	SD	N	Ave	SD	Type	Value	*p*
Beck et al. (1996). J Bone Miner Res 11(5):645-53	tibia-distal	DXA	23	296	41	587	333	44	% Difference	10.90%	0.0001
Beck et al. (1996). J Bone Miner Res 11(5):645-53	femur-mid	DXA	23	487.3	64.7	587	536.5	67.8	% Difference	9.20%	0.0008
Milgrom et al. (1988). Clin Orthop(231):216-21	tibia-distal	X-ray	58	386	65	228	395	60	Wilcoxon Rank Sum		0.014

Table 6. A summary of initial fitness level risk factor results found in the literature.

Measure	StFx Rate	Ntotal	Signficance	Source
Miles/week				
> 25 mi/wk	3.0%	100		Montgomery et al. (1989). Med Sci Sports Exerc 21(3):237-43
4-25 mi	5.0%	279	NS	
< 4 mi/wk	11.5%	96	P = 0.027	
Frequency of sweating during exercise				
Quite a lot/all the time	1.6%	595		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
Fairly often	3.6%	408	95% CI (0.99-5.15)	
Occasionally/never	8.3%	283	95% CI (2.36-10.8)	
Quite a lot/all the time	1.8%	493		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
Fairly often	5.1%	376	95% CI (1.27-6.05)	
Occasionally/never	6.2%	209	95% CI (1.48-7.85)	
Self-reported Fitness				
Very good/excellent	1.8%	395		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
Good	3.6%	649	95% CI (0.82-4.91)	
Fair/poor	6.5%	278	95% CI (1.45-9.09)	
Very good/excellent	2.1%	187		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
Good	3.3%	573	95% CI (0.53-4.50)	
Fair/poor	5.7%	315	95% CI (0.89-7.52)	
# Exercises/Week				
= 4 /wk	2.6%	658		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
3	3.2%	300	95% CI (0.54-2.72)	
= 2	6.9%	328	95% CI (1.28-4.65)	
= 4 /wk	3.4%	531		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
3	3.2%	275	95% CI (0.44-2.12)	
= 2	5.1%	272	95% CI (0.77-3.01)	

Measure	StFx Rate	Ntotal	Signficance	Source
Run Experience (months)				
> 3	1.6%	263		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
2-3	2.3%	464	95% CI (0.45-4.50)	
= 1	5.9%	343	95% CI (1.25-10.50)	
None	5.7%	216	95% CI (1.14-10.65)	
> 3	2.4%	165		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
2-3	4.4%	384	95% CI (0.62-5.34)	
= 1	3.7%	405	95% CI (0.51-4.53)	
None	4.0%	124	95% CI (0.46-6.07)	
Initial 1.5 mi Run Time				
Q1 8:10-10:29	2.3%	267		Shaffer et al. (1999). Am J Epidemiol 149(3):236-42
Q2 10:30-1:19	1.9%	255	95% CI (0.27-2.82)	
Q3 11:20-12:14	3.9%	284	95% CI (0.65-4.6)	
Q4 12:15-17:10	7.0%	272	95% CI (1.26-7.66)	
Ball Sports Played				
No ball sports	28.9%	263		Milgrom et al. (2000). Am J Sports Med 28(2):245-51
Ball sports	13.2%	129	95% CI (0.210-0.664)	
No ball sports	27.0%	304		Milgrom et al. (2000). Am J Sports Med 28(2):245-51
Ball sports	16.7%	90	95% CI (0.294-0.996)	
No ball sports	18.8%	277		Milgrom et al. (2000). Am J Sports Med 28(2):245-51
Ball sports	3.6%	55	95% CI (0.039-0.692)	
Minutes of Exercise Per Week				
428.0±354.0 min/wk	100%	27		Lauder et al. (2000). Arch Phys Med Rehabil 81(1):73-9
291.6±187.0 min/wk	0%	158	P < 0.5	

2.2.2 Performance

As mentioned earlier, the primary goal of training is to maximize physical fitness while minimizing injuries sustained. Thus, the TOP model incorporates both an injury and performance model, allowing users to understand how injury and performance are interrelated.

This section details the performance part of the TOP model. As previous reports have not covered performance, we review existing models found in the literature followed by details of the TOP performance model.

Literature Review

The body's ability to perform is dependent on many highly complex chemically-based systems which convert ATP and oxygen to muscle force. In addition, there are substantial neurological factors such as skill and motivation. While a complete model of the physiology involved with athletic performance would be a substantial scientific contribution, such a model would be too complex to be useful as a predictive tool. In addition, while much is known about the chemical processes involved in exercise physiology, how these complex systems interact under the stresses of exercise has not been fully elucidated. Thus, we chose to investigate more empirically-based approaches, where simple equations are used to describe the observed overall performance enhancements.

There are several different models presented in the literature to predict performance. However, we only cover those that are the basis of the TOP model in more detail (see Table 7).

Table 7. A summary of performance models found in the literature.

Source	Data Summary
(Morton et al. 1990)	The "Banister" model. Uses exponential decay fitness and fatigue components with reasonable results.
(Fitz-Clarke et al. 1991)	Demonstrates how the Banister model can be used to optimize training to reach a desired performance level in a specified amount of time. Introduces the idea of influence curves.
(Vandewalle et al. 1997)	Investigates the physiological meanings of the parameters in the Critical Power model. Finds that this model is best as an aerobic fitness indicator.
(Jenkins and Quigley 1993)	The influence of high-intensity exercise on the "Critical Power" model. A more detailed review of the model can be found in Vandewalle et al. (1997).
(Busso 2003)	Banister model with a time varying fatigue component to account for increased fatigue from multiple training sessions. Appears more realistic than previous versions.

R. H. Morton, J. R. Fitz-Clarke, and E. W. Banister. Modeling human performance in running. J.Appl.Physiol. 69 (3):1171-7, 1990.

In this model, originally proposed by Banister et al. (1975) and referred to as the "Banister Model," training is quantified using duration and heart rate and includes a weighting factor to emphasize high intensity training. The model has two components: fitness and fatigue. Both are exponential decay type equations that increase or reduce the ability to perform at a given time based on the training dosage history. See Figure 4.

In this model, training is quantified by a pseuointegral (training impulse based on minutes of exercise) based on a normalized heart rate.

$$\mathrm{w}(t) = D\left(\frac{\mathrm{HR_{ex}}\text{-}\mathrm{HR_{rest}}}{\mathrm{HR_{max}}\text{-}\mathrm{HR_{rest}}}\right)Y \qquad 15$$

where D is the duration of exercise, HR_{ex} is the average hear rate during exercise, HR_{rest} is the resting heart rate, and HR_{max} is the maximal HR. The weighting factor Y is to emphasize high intensity training and is defined as

$$Y = e^{bx} \qquad 16$$

where x equals the heart rate ratio term of Eqn 15 and b is a coefficient that depends on gender (1.92 for men and 1.67 for women).

In the simplified model of Figure 4, two factors, fitness g(t) and fatigue h(t), are recurrently affected each time training w(t) is undertaken, so that

$$\mathrm{g}(t) = \mathrm{g}(t-i)e^{-i/t_1} + \mathrm{w}(t) \qquad 17$$

and

$$\mathrm{h}(t) = \mathrm{h}(t-i)e^{-i/t_2} + \mathrm{w}(t) \qquad 18$$

where g(t) and h(t) are arbitrary fitness and fatigue response levels, respectively, at the end of day t, i is the intervening period between the current days' training and that previously undertaken, and τ_1 and τ_2 are decay time constants of these respective effects.

Model performance at time t, p(t), is given by the simple linear difference

$$\mathrm{p}(t) = k_1\mathrm{g}(t) - k_2\mathrm{h}(t) \qquad 19$$

where k_1 and k_2 are positive dimensionless weighting factors for fitness and fatigue, respectively.

In this study, the model had good predictive power for two subjects tested for maximal performance. The dosage was variable, not block and the training lasted 28 days. This was followed by a 50 day cessation of training (other than the performance tests). The model parameters were derived using a least-squares regression and were able to predict performance reasonably well ($r^2 = 0.71$, $p = 0.001$ and $r^2 = 0.96$, $p = 0.0001$ for the two subjects). Independent verification of the model by application with the derived parameters to new subjects was not done.

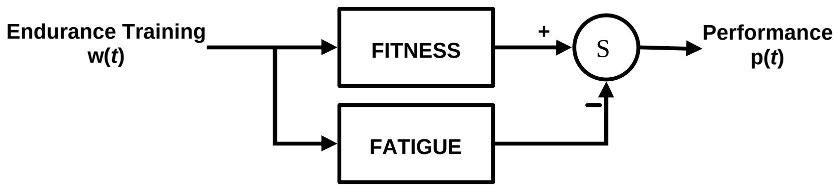

Figure 4. Simple 2-component systems model of training and performance. Diagram shows how training input w(*t*) affects both fitness and fatigue. The summer (S) combines these responses, fitness positively and fatigue negatively, into a single performance output p(*t*) (Morton et al. 1990).

T. Busso. Variable dose-response relationship between exercise training and performance. Med.Sci.Sports Exerc. 35 (7):1188-1195, 2003.

This article proposes a modification to the Banister model and tests it (and three previous variations) using a cycling ergometer training regiment. As mentioned in the above review of Morton et al. (1990), the original model is defined by a transfer function composed of two first-order filters characterized by the two gain terms k_1 and k_2, and the two time constants τ_1 and τ_2 (labeled Model 2-Comp in this study). To test the statistical significance of the second or fatigue component, the two-component model was compared with a systems model comprising only one first-order filter (Model 1-Comp) with an impulse response $k_1 e^{-t/t_1}$. Another third-order model (Model 3-Comp), proposed by Calvert et al. (1976), has two negative components and one positive component to single out the fatigue effect on the time course of training adaptation. The impulse response of this systems model is $k_1\left(e^{-t/t_1} - e^{-t/t_1'}\right) - k_2 e^{-t/t_2}$. For each model, the performance p(t) is obtained by the convolution product of the training doses w(t) with the impulse response added to basic level of performance noted p*. W(t) is considered to be a discrete function, i.e., a series of impulse each day, w^i on day *i*. The convolution product becomes a summation in which model performance $\hat{p}^n$ on day n is estimated by mathematical recursion from the series of w^i. $\hat{p}^n$ is thus estimated for models used in this study as follows:

$$\text{Model 1-Comp: } \hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i e^{-(n-i)/t_1} \quad 20$$

$$\text{Model 2-Comp: } \hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i e^{-(n-i)/t_1} - k_2 \sum_{i=1}^{n-1} w^i e^{-(n-i)/t_2} \quad 21$$

$$\text{Model 3-Comp: } \hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i \left[e^{-(n-i)/t_1} - e^{-(n-i)/t_1'} \right] - k_2 \sum_{i=1}^{n-1} w^i e^{-(n-i)/t_2} \quad 22$$

The new model proposed in this study assumes that the gain term for the negative component is a state variable varying over time in accordance with system input. Performance output for the model proposed in this study is computed as follows:

$$\hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i e^{-(n-i)/t_1} - \sum_{i=1}^{n-1} k_2^i w^i e^{-(n-i)/t_2} \quad 23$$

in which, the value of k_2 at day *i* is estimated by mathematical recursion using a first-order filter with a gain term k_3 and a time constant τ_3

$$k_2^i = \sum_{j=1}^{i} w^j e^{-(i-j)/t_3} \quad 24$$

The daily training quantity was computed in arbitrary units from work done during training sessions and trials. The work done during warm-up and recovery was not considered in the computation. The tests to measure P_{lim5}' (average power during a 5 minute all-out cycling ergometer exercise) and $\dot{V}O_{2max}$ were both arbitrarily ascribed to 100 training units (t.u.). Each 5-min bout of exercise for training sessions was weighted by intensity referred to P_{lim5}' (i.e., mean power output / P_{lim5}' $\times$ 100). A training session composed of four bouts of exercise at 85% of P_{lim5}' would be thus ascribed to $4 \times 85 = 340$ t.u. The regiment for this experiment consisted of 2 weeks of performance measures only (no training) 8 weeks of 3 sessions / week of training, a week of performance testing only, followed by 4 weeks of 5 sessions / week and another two weeks of performance testing only.

The results show that the most accurate version contains a fatigue component varying in time to account for increases in the fatigue effect from repeated training sessions (Proposed Model, Table 8). However, the accuracy of this model under different training regiments is unknown.

Table 8. Indicators of goodness-of-fit of performance for various systems models of training effects. Results are the average from six subjects.

Model 1-Comp		Model 2-Comp		Model 3-Comp		Proposed Model	
Adj. R^2	SE	Adj. R^2	SE	Adj. R^2	SE	Adj. R^2	SE
0.857±0.042	10.31±1.56	0.885±0.048	9.22±2.27	0.885±0.049	9.20±2.27	0.944±0.011	6.47±0.71

H. Vandewalle, J. F. Vautier, M. Kachouri, J. M. Lechevalier, and H. Monod. Work-exhaustion time relationships and the critical power concept. A critical review. J.Sports Med.Phys.Fitness 37 (2):89-102, 1997.

This article is reviews the “Critical Power” model, an empirical model based on the observation that there is a linear relationship between the exhaustion time (t_{lim}) of a local exercise (e.g., flexions or extensions of the elbow or the knee) performed at different constant power outputs (P) and the total amount of work performed at exhaustion (W_{lim}):

$$W_{\mathrm{lim}} = P \times t_{\mathrm{lim}} = a + b \times t_{\mathrm{lim}} \qquad 25$$

The slope b of the W_{lim} linear relationship (Figure 5-A) represents the power output which can be sustained during a long time. Indeed, the relationship between P and t_{lim} is a hyperbola (Figure 5-B) whose asymptote is equal to b:

$$t_{\mathrm{lim}} = a / (P - b) \qquad 26$$

In theory, the exhaustion times t_{lim} corresponding to exercises whose power output are equal to (or lower than) slope b are infinite. Consequently, power corresponding to slope b was called critical power. However, experiments suggest that critical power should be considered an index of local aerobic endurance rather than a strength endurance index.

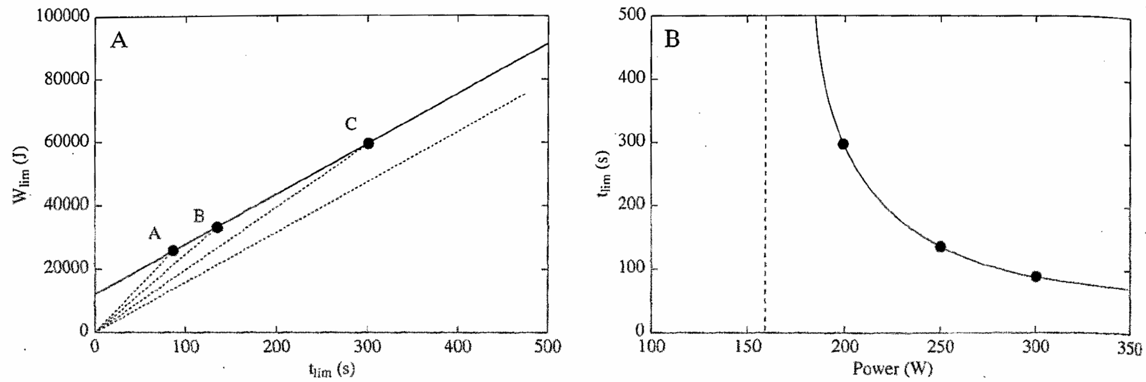

Figure 5. A) Linear relationship between exhaustion time (t_{lim}) and the cumulated work (W_{lim}) performed at the end of exercise. A, B and C correspond to three exercises performed at different constant power. Dots A, B and C are aligned. The dotted lines correspond to the linear increases of the work performed during an exercise at constant power output up to exhaustion. B) Hyperbolic relationship deduced from the linear t_{lim}-W_{lim} relationship. The vertical dotted line corresponds to critical power. (See Vandewalle et al. 1997)

The assumptions for this model are that (1) fatigue is from metabolic factors, (2) mechanical efficiency or energy cost is independent of power or velocity, and (3) the y-intercept corresponds to an energy store which is depleted at exhaustion and whose value is independent of exhaustion time. However, these assumptions are probably not valid for very short or very long exercises. Exercise from 1-15 minutes seems to follow the model well.

Because the relationship between W_{lim} and t_{lim} is not perfectly linear, the slope and y-intercept depends on the range of values tested. Given the hyperbolic relationship between t_{lim} and power or velocity, a small variation in power and velocity induces a large difference in the estimated value of t_{lim}. Thus, the model is not very good at predicting time to exhaustion. However, the slope b is relatively insensitive to errors. Thus, the model can be used as a measure of aerobic fitness. The y-intercept (anaerobic capacity) is more sensitive to errors.

TOP Performance Model

The literature review suggests that performance capability at a given instant in time is dependent on two competing components: performance enhancement and fatigue. The studies reviewed used a dose-response model with favorable results where the two competing components are exponential decay functions of varying complexity. For this initial TOP model, we base our model on the simplest form of these equations. See Equation 21.

There are two other components of performance in the military that are not explicitly accounted for by the models suggested in the literature. These are (1) improvements in performance due to increases acquaintance or skill and (2) the reduction in improvements as subjects approach their maximum performance level. We include terms to account for these factors.

The ability of a model to predict changes in performance is dependent on choosing a reasonable dosage quantity. Being unable to find guidance on this topic, we use a dose based on the Critical Power model until a more thorough literature review can be conducted.

Performance modeling of a given activity

Because training and performance in the military can encompass different activities and training methods, we sought to develop a generic model that was applicable to different situations. In a manner similar to the treatment of heart rate by Morton (1990) (see Equation 15), we normalized performance by assuming that any performance for a given activity can be scored and that there is a maximum and minimum value. Thus, normalized performance pp can be calculated as:

$$\mathrm{pp}=\frac{\mathrm{p_{score}}-\mathrm{p_{score}^{min}}}{\mathrm{p_{score}^{max}}-\mathrm{p_{score}^{min}}} \qquad 27$$

where $\mathrm{p_{score}^{max}}$ and $\mathrm{p_{score}^{min}}$ are the theoretical highest and lowest scores possible.

We note that the equivalent mathematical term to the pseudointegrals used in the Banister models is the convolution function $\otimes$. Thus, if we define

$$\mathrm{g}_i = k_i e^{-t/t_i} \qquad 28$$

and include an improvement penalty and skill factor, then the general form of the performance equation becomes

$$\mathrm{pp}=\mathrm{pp}_0+\left\{(1-\mathrm{pp})^n\cdot \mathrm{g}_1\otimes \mathrm{w}-\mathrm{g}_2\otimes \mathrm{w}\right\}K \qquad 29$$

where pp_0 is the pre-training performance score, $(1\text{-pp})^n$ is the penalty function that makes it more difficult to improve as performance approaches maximum, g_1 is the function describing performance enhancement, g_2 describes long-term fatigue, and w is the training dose. K is the skill term and is of form:

$$K=K_0+(1-K)^m\cdot \mathrm{g}_3\otimes \mathrm{w} \qquad 30$$

where K_0 is the initial skill level and $(1\text{-}K)^m$ is a penalty function analogous to the one in Equation 29 for performance. Thus, skill K is a function of the daily dosage of an activity. The parameters will depend on the activity, muscle groups involved, etc.

Training Dose, w

The definition of dose w will depend on the performance measure. Unfortunately, there is a lack of guidance on what the basis of dose should be. Heart rate, work and distance traveled are all potential components of a dosage function and a more in-depth literature review is needed. To demonstrate how the TOP model would function, we arbitrarily used the Critical Power concept (Vandewalle et al. 1997) to help define training dose for marching and running. Critical Power was chosen because it describes two important characteristics of exercise. First, critical power describes the maximum power than can be sustained through the aerobic system. Second, the Critical Power concept notes that the amount of short-term anaerobic work that can be performed is fixed and is independent of the power or work rate. Thus, it is possible to define training intensity as the amount of anaerobic work utilized during a marching or running exercise. In contrast, aerobic work can be sustained for a very long time, making it difficult to determine the training work rate intensity. A more complete review of potential training dosage measures is needed and in the future, individual muscle performance definitions should be developed.

For this preliminary model, the dosage w that would illicit a training response was assumed to be proportional to the anaerobic work performed during an exercise. This requires an estimate of the maximum amount of anaerobic work available, $\mathrm{w}_{\mathrm{exh}}$. By knowing the power level of maximal aerobic work pwr*, i.e., critical power, the anaerobic work available until exhaustion can be defined as:

$$\mathrm{w}_{\mathrm{exh}} = \left(\mathrm{pwr}_{\mathrm{tot}} - \mathrm{pwr}^*\right) t_{\mathrm{lim}} \qquad 31$$

where t_{lim} is the time until exhaustion and $\mathrm{pwr}_{\mathrm{tot}}$ is the total power. Realistically, $\mathrm{w}_{\mathrm{exh}}$ and pwr* are functions of training time but are ignored in this model. In Figure 5, Vandewalle et al. (1997) describes a cycling study where time, power, and work until exhaustion were measured. The approximate values for exercise A, B, and C can be found in Table 9. Using equations 25 and 26, we estimate critical power to be 160 watts. Using Equation 31, $\mathrm{w}_{\mathrm{exh}}$ is approximately 12,100 J.

Table 9. Approximate values for the data points found in Figure 5.

Exercise	t_{lim} (sec)	w_{lim} (J)	Power (watts)
A	87	26,100	300
B	135	33,750	250
C	300	60,000	200

We now demonstrate how a normalized dosage can be derived. In U.S. Marine Corps training, a common initial performance measure is the 1.5 mile run. We assume a speed of 5 m/s for this example. To estimate anaerobic work for nonexhaustive running, we defined *ppd* as the total amount of work per distance per body weight and *ppd** as the amount per distance per body weight sustainable by the aerobic system. Anaerobic work normalized to body weight (w_{AA}) can then be estimated if the gait velocity and time is known:

$$w_{AA} = \left(ppd - ppd^* \right) \cdot v \cdot t \qquad 32$$

If pwr* is 160 watts, *ppd** is estimated to be 0.46 J/kg/m for a 70 kg subject running at 5 m/s. By definition, w_{AA} is the total anaerobic work w_{exh} divided body weight or 172.8 J/kg. Using the derived values for w_{AA} and *ppd** in Equation 32, *ppd* is calculated to be 0.53 J/kg/m for a 1.5 mile run.

Because *ppd* is normalized to body weight, we appeal to Equation 32 to adjust w_{AA} for different load carriage:

$$w_{AA} = \left\{ \left(1 + h\right) ppd - ppd^* \right\} \cdot v \cdot t \qquad 33$$

where *h* is the additional weight as a percent of body weight. Thus, Equation 33 is used as a training dose where the value is based on the amount of anaerobic work used during running and can account for changes in work due to added weight. Because w_{AA} is normalized to body weight, Equation 33 is applicable to different subjects. The value for *ppd* will change depending on the activity.

In summary, the TOP performance model attempts to account for changes due to enhancement, fatigue, and skill by using a dose-response type of model. Because the physiology of exercise is too complex to model effectively, an empirically-based approach was used. The model also demonstrates the use of anaerobic work as a possible dose measure. However, additional development of a more realistic dose will need to be done.

2.2.3 Metabolic Cost

This section reviews existing metabolic cost models and describes the approach taken for the TOP metabolic cost model.

Metabolic cost is another important measure for military training—it provides guidance on nutritional needs, energy expenditure, and weight control. Thus, while energy cost could be a sub-component of the performance model, there is sufficient interest in metabolic cost alone to warrant a separate model. Technically, metabolic cost is an energy measure. However, under steady-state aerobic conditions, oxygen consumption is often used.

Metabolic cost varies with activity and effort, primarily because of the different muscle groups involved. Thus, estimating metabolic cost during basic training is difficult because of the large number of different activities. One approach is to measure metabolic cost directly from as many variations of a given activity as possible, creating a lookup table and interpolating for situations not measured directly (e.g., Pandolf et al. (1977) estimates cost for walking on different grades and terrain). Unfortunately, this method requires a large number of experiments and does not offer guidance as to how metabolic cost may change under new situations. In addition, this method often leads to complex equations that are unable to make adjustments for individual variations in fitness (other than weight). Another approach is to model the underlying phenomenon responsible for metabolic cost—the muscle (e.g., Kram and Taylor 1990). This should allow predictions of metabolic cost for a wider variation of a given movement without the need of comprehensive tests and adjust for different individuals. However, this method still requires a thorough biomechanical analysis of each movement to determine the contribution of different muscle groups and an objective method to measure individual variation in muscle group characteristics.

Literature Review

Clearly, there are too many activities in basic training to accurately calculate a daily metabolic cost initially. Instead, we focus on the two main exercises of basic training—running and marching.

B. L. Sih and James H. Stuhmiller. The metabolic cost of force generation. Med.Sci.Sports Exerc. 35 (4):623-629, 2003.

In Sih and Stuhmiller (2003), the literature was reviewed and evidence presented that supports metabolic cost being directly related to the mechanical work done at the muscle level. The paper showed that an equation exists that estimates metabolic cost above resting ($\dot{E}$, watts) based on muscle force and rate of application:

$$\dot{E} = c \cdot \overline{F} \cdot \dot{N} \qquad 34$$

where $\overline{F}$ (N) is average vertical force on one leg (body weight / 2), $\dot{N}$ (steps / sec), and *c* is a constant, estimated to be 0.30±0.05 J / N / step for bipeds. The coefficient was derived using 12 species of bipeds (11 avian and human) and the coefficient was found to be constant (but different) depending on activity and number of legs (biped versus quadruped). See Figure 6.

The paper theorizes that different coefficients for different movements can be explained by the various contraction length changes and / or mechanical advantage differences with each movement. Movements where contraction length changes are minimum or the "effective mechanical advantage" is large (i.e., running), a small cost coefficient is seen. In contrast, a large coefficient is found in movements such as cycling, where muscle goes through a larger contraction distance with less mechanical advantage. Thus, if the muscle length change and mechanical advantage can be accounted for, a universal coefficient will emerge, allowing the calculation of the metabolic cost of a wide variety of movements from a single relationship (Equation 34). Unfortunately, only a few movements have been analyzed of which running is the most applicable to basic training. Also, there was insufficient data in the literature to determine the cost coefficient *c* for marching.

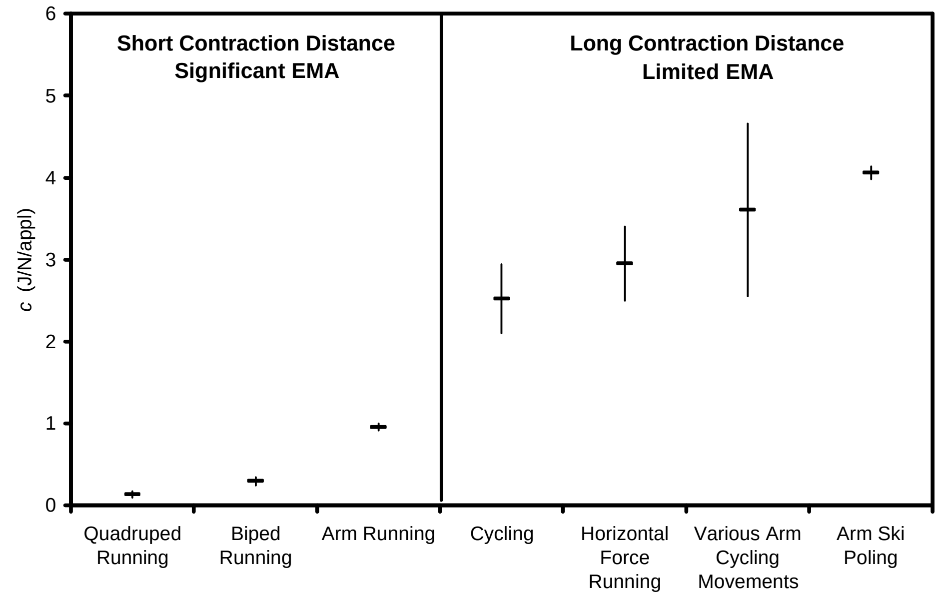

Figure 6. The mean value for the cost coefficients of seven different analyses. Movements where the effective mechanical advantage (EMA) is large (bones aligned with the external force increase the muscle toe external force moment arms ratio about a joint) and muscle contraction distance is short are approximately 5´ smaller than those with reduced EMA and increased contraction distance. Error bars represent 1 SD. (See Sih and Stuhmiller 2003)

K. B. Pandolf, B. Givoni, and R. F. Goldman. Predicting energy expenditure with loads while standing or walking very slowly. J.Appl.Physiol 43 (4):577-581, 1977.

In a previous paper, the authors presented a formula to predict metabolic rate for walking and load carrying but the slowest speed tested was 0.7 m/s. This paper (Pandolf et al. 1977) expands the range of the equation to 0.2 m/s as well as standing still. Parameters of the original equation include body weight, external load, speed, terrain, and grade.

Six male subjects were used and metabolic rate was measured for a variety of speeds and loads only. In addition, ten different male subjects who stood with different pack weights were analyzed. Sufficient time was allotted to allow steady-state to be reached. The updated equation is:

$$M_w = 1.5W + 2.0(W+L)(L/W)^2 + h(W+L)(1.5V^2 + 0.35GV) \qquad 35$$

where M_w is the metabolic cost as if walking (watts), W is nude body mass (kg), L is clothing and equipment weight (kg), h is a terrain factor, V is walking velocity (m/s) and G is grade (%). h is 1.0 for treadmill walking. Valid ranges for the variables can be found in Table 10.

Table 10. Range of acceptable parameter values for Equation 35.

Variable	Range
Extra Load, *L*	0 – 40 kg
Walking Velocity, *V*	0 – 2.4 m/s
Grade, *G*	0 – 24 %
Terrain Factor, *h*	1.0 – Treadmill or Blacktop Surface
	1.1 – Dirt Road
	1.2 – Light Brush
	1.3 – Hard Packed Snow
	1.5 – Heavy Brush
	1.8 – Swampy Bog
	2.1 – Loose Sand
	2.5 – Soft Snow (15 cms)
	3.3 – Soft Snow (25 cms)
	4.1 – Soft Snow (35 cms)

TOP Metabolic Cost Model

The use a single function such as Equation 34 to calculate metabolic cost based on muscle force estimates would be ideal. However, a thorough analysis of the muscles involved in many of the military training exercises has not been done. Section 5.1-Muscle Groups (pg. 46) begins the process by identifying the prominent muscle groups used in different activities. Thus, only running and walking were considered in initial metabolic cost model, using the two different equations reviewed above. We hope that future variations will be based on muscle force as more data becomes available.

For running, Equation 34 requires body weight to estimate force *F* and step rate. In a previous report (Woodmansee et al. 2004), a regression equation to predict step rate from run speed was derived from an extensive review of the literature:

$$SR = 0.0209 \cdot V^2 + 0.0081 \cdot V + 0.8679 \qquad 36$$

where *SR* is step rate (steps / sec) and *V* is running velocity (m / s). The velocity range used to derive this equation is 1-10.16 m / s. Approximately 200 subjects are represented (r^2 = 0.94). Thus, given body weight and running speed, the TOP model estimates metabolic cost for running using a muscle force-based equation.

Unfortunately, there is insufficient information in the literature at this time to formulate muscle force values during walking. During walking (and marching) weight is supported primarily through the bones, rather than the muscles. Thus, ground reaction forces are not directly related to muscle force and we require a different means of estimating the force. Unable to find sufficient information on muscle forces for marching to apply Equation 34, we use the more complex Pandolf equation (Equation 35), which requires body and load weight, velocity, terrain, and grade measures. For the TOP model, we assume a blacktop surface (*h* = 1.0) and a grade of 0%.

In summary, the metabolic cost component of the TOP model estimates energy costs for two exercises: running and marching. Clearly, there are additional exercises conducted during basic training (see Section 5.3-Exercises, pg. 53) but we lack sufficient information to estimate metabolic cost for these other activities. Future work should focus on estimating muscle force for different movements, allowing the use of Equation 34 to estimate metabolic cost.

3. Model Demonstration

The TOP model was implemented in MatLab (version 7.0). While there is insufficient data to assess the accuracy of the model at this time, we can still demonstrate its feasibility. In addition, we use this demonstration to confirm that performance and injury trends predicted by the model are in agreement with those observed during actual training. Thus, the purpose of this section is to show how the model, with both performance and injury components, can be a tool to better design train regiments.

3.1 Inputs

Input data for the TOP model is used to determine initial conditions and training profiles as well as calibration of model parameters. All data comes from MCRD training data quantified previously (see Sih et al. 2003). Unfortunately, none of the MCRD training sets available were complete such that all three TOP components (stress fracture, performance, and metabolic cost) could be modeled from the same set of data. Thus, to generate “individuals” with sufficient information for the TOP model, data from different training sessions were combined.

3.1.1 Training Regiment

The training regiment used in this demonstration is based on the Training Outline Plan for the 1994-95 MCRD Parris Island recruits. This plan was chosen because it was the most complete and included daily stress fracture rates. As described in the report (Sih et al. 2003), training distance (Figure 7) was converted into steps using literature derived regression equations (Woodmansee et al. 2004). In addition, performance gains were assumed to be dependent on anaerobic work only (see Training Dose, *w*, pg. 23).

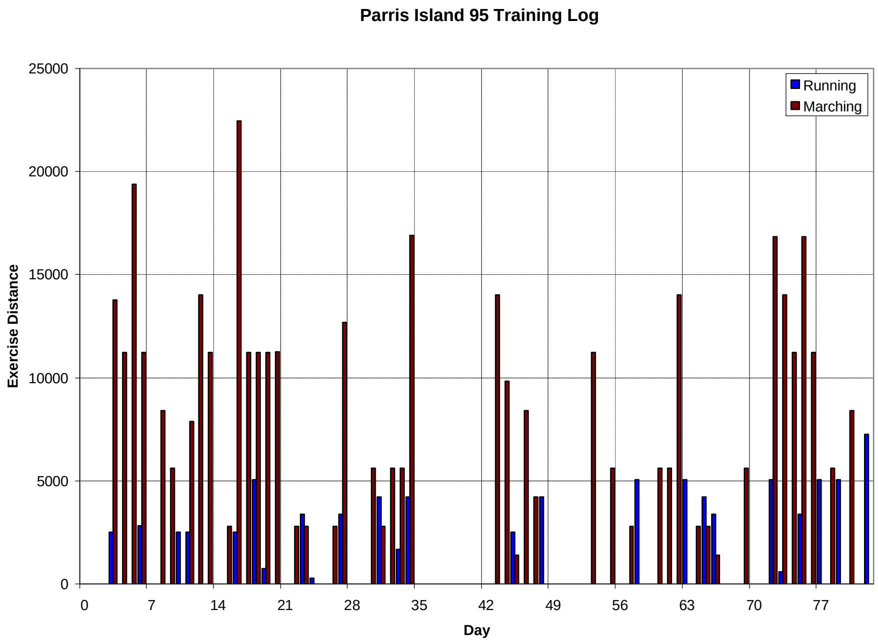

Figure 7. Estimated daily distance traveled while marching and running used in the TOP model demonstration. Distances based on the 1994-95 MCRD Training Outline Plan for Parris Island (Sih et al. 2003).

3.1.2 Subject Data: Initial and Final Conditions

For this demonstration, data was combined to create 100 pseudo-subjects. Subject weights were from the Parris Island dataset and estimated 3.0 mile run times from 2003 MCRD San Diego (J. Reading, personal communication, April 8, 2003). For comparison purposes and model parameter calibration, daily stress fracture rates from Parris Island and Day 18 and Day 77 runtimes from San Diego were used. There was no metabolic cost estimates available.

3.1.3 Model Parameters

Table 11 and Table 12 list the parameters used in the stress fracture and performance components of the TOP model, respectively. Additional details on the parameters and the equations they correspond to can be found in Section 2.2-Model Components (pg. 5). The parameters for the metabolic cost component are unchanged from the originally published values (see Section 2.2.3-Metabolic Cost, pg. 25).

Table 11. List of parameters used in the overuse injury component of the TOP model. Values are based on those reported by Martin (2001).

Symbol	Value	Units	Description
k_D	52505	mm/mm^2	damage formation rate coefficient
q	4	dimensionless	exponent on strain range
f_{a0}	0.0064	# of $BMU/mm^2/day$	equilibrium activation frequency
f_{a0max}	0.5	# of $BMU/mm^2/day$	maximum activation frequency
k_R	0.151	mm^2 day/BMU	coefficient for activation frequency
r_c	0.095	mm	cement line radius
F_s	5	dimensionless	BMU targeting factor
T_R	5.1	days	BMU resorbing period
T_I	1.43	days	BMU reversing period
T_F	62	days	BMU refilling period
Q_C	0.0055	mm^2/day	BMU resorption rate
Q_B	4.00E-04	mm^2/day	BMU refilling rate rate
E_0	20	GPa	maximum bone elastic modulus
M_w	0.001	mm/mm^2	rate of woven bone creation
D_C	0.004	mm/day	critical damage level for modeling

Table 12. List of parameters used in the performance component of the TOP model.

Symbol	Value	Units	Description
p^{score}_{min}	15 min	test dependent	minimum performance score
p^{score}_{max}	27.5 min	test dependent	maximum performance score
n	1	dimensionless	enhancement difficulty exponent
k_1	0.05	dimensionless	performance enhancement function coefficient
t_1	40	days	performance enhancement function time constant
k_2	0.005	dimensionless	fatigue function coefficient
t_2	10	days	fatigue function time constant
k_3	0.05	dimensionless	skill function coefficient
t_3	40	days	skill function time constant
m	1	dimensionless	skill improvement difficulty exponent

3.1.4 Risk Factor Distribution

Unable to find a suitable means of quantifying the distributions needed to weight the risk factors (i.e., S_{diff}, S_{risk}, S_{perf}, S_{fatigue} used in Equation 4), an extreme value or Gumbel distribution function (Figure 8) was used for initial performance S_{perf}. The remaining distributions were set to one (no effect) for this demonstration.

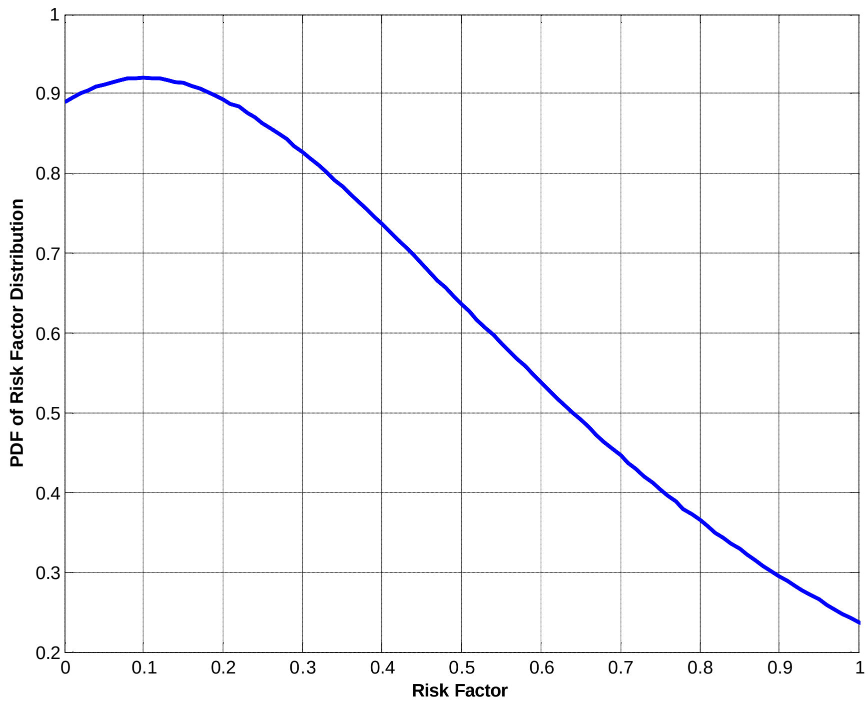

Figure 8. Theoretical performance risk factor probability density function used in the TOP model to increase the likelihood of a stress fracture.

3.2 Results

3.2.1 Stress Fracture

On an individual recruit basis, as training progressed damage levels increased with those subjects having a higher risk of stress fracture and low initial performance sustaining the most damage. See Figure 9. The current form of the model suggests that there is insufficient time or rest during the 84 days of training to reduce damage.

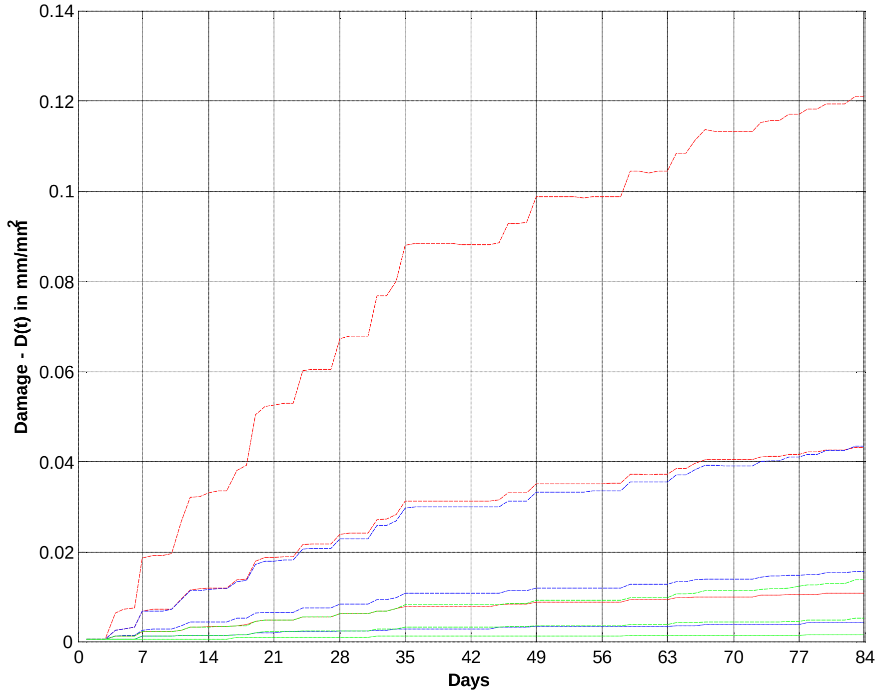

Figure 9. Damage level progression for a variety of different theoretical individuals undergoing the Parris Island training regiment. The red line represents a subject with a high risk factor and little previous training. Lines with less damage are from subjects with a lower risk and better initial performance.

3.2.2 Performance

In Figure 10, the predicted change in performance with time for recruits of three different initial fitness levels is plotted. The physically fit subject maintains his superior score but the largest improvements come from the unfit recruit.

Performance enhancement for a population is most easily shown using a cumulative density distribution where the x-axis represents performance scores and the y-axis indicates the proportion of recruits with scores equal to or less than a given score. From Figure 11, it is apparent that performance is enhanced for all recruits with slower recruits (both the model and observed) increasing their performance to a much greater degree than those subjects with a higher initial score.

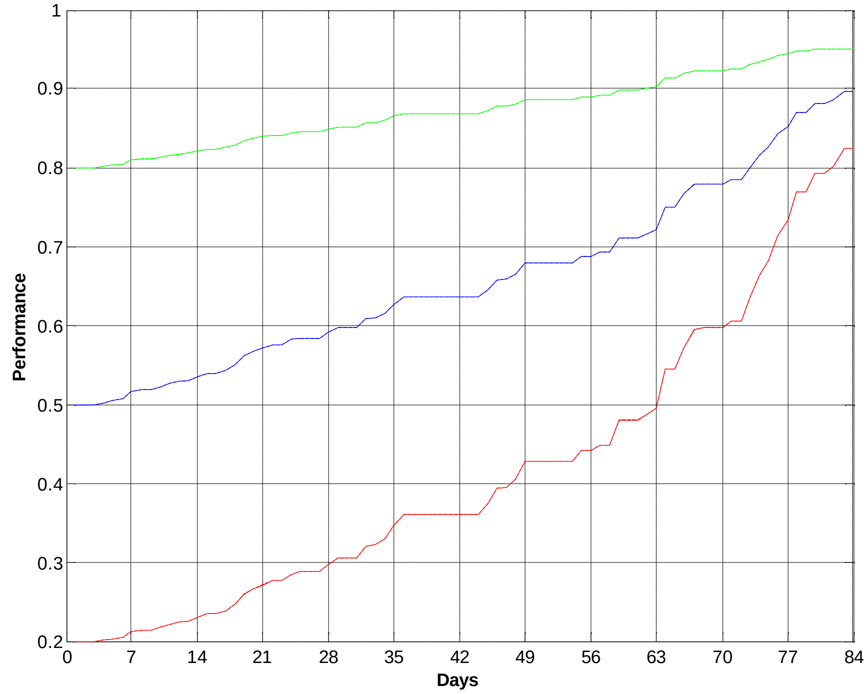

Figure 10. Predicted changes in performance during training for three theoretical subjects. Red, blue, and green represent subjects with poor, medium, and good initial fitness levels, respectively.

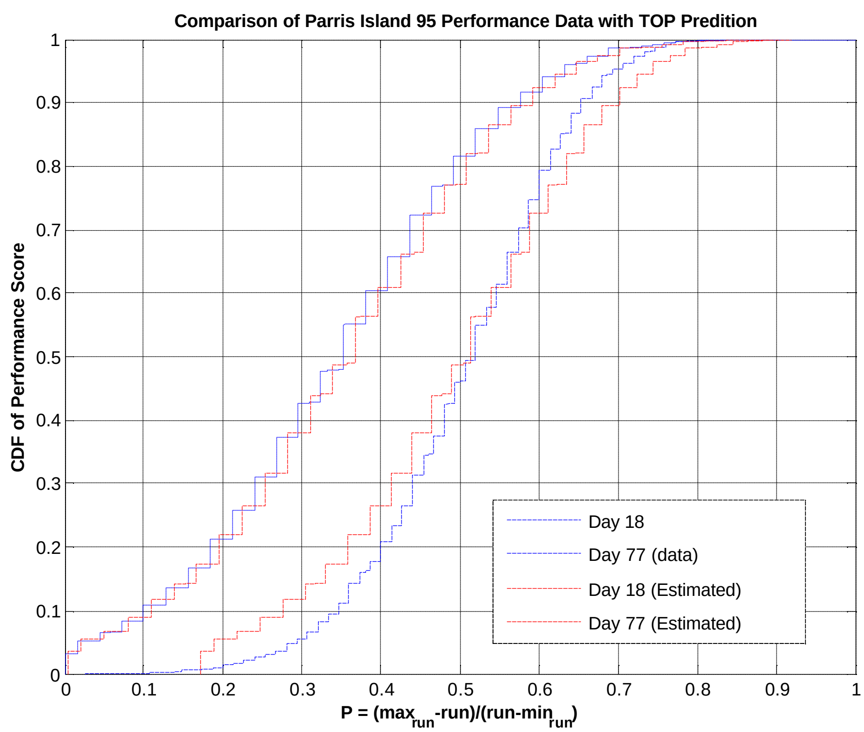

Figure 11. Cumulative density distribution of performance scores at training day 18 and day 77. Blue lines are recorded recruit's performance scores. Red lines are the TOP model predictions.

3.2.3 Metabolic Cost

Figure 12 shows the estimated daily metabolic cost due to marching and running. As expected, the daily value is primarily dependent on the distances traveled with a small amount of variation due to the different body weights of the subjects. The large single day energy expenditures are due to road marches, which involve load carriage.

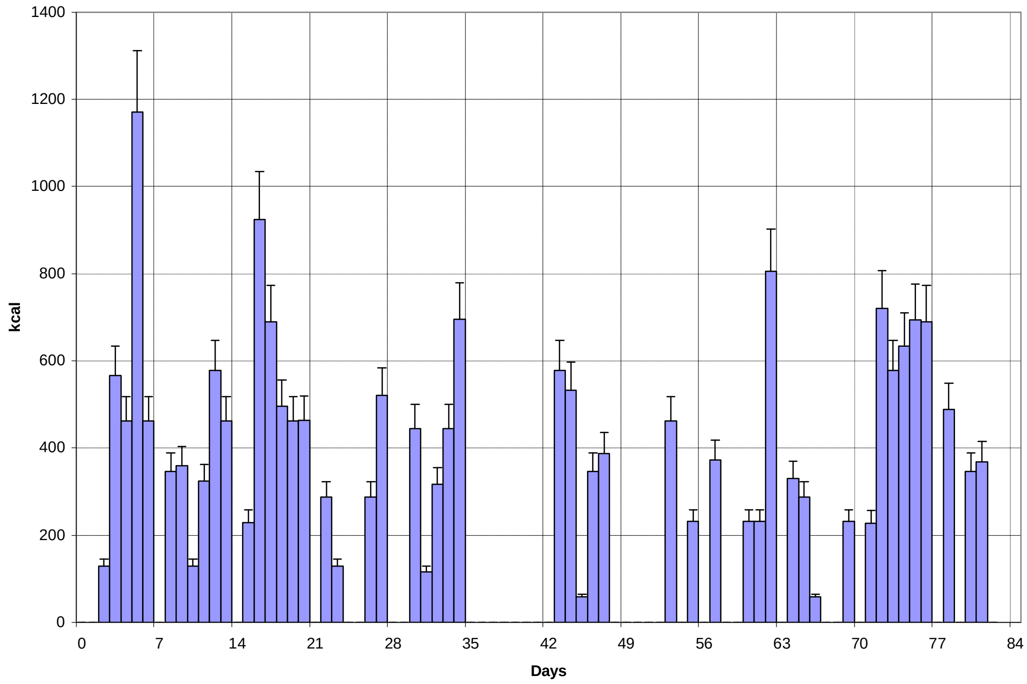

Figure 12. Estimated metabolic cost for recruits subjected to the Parris Island training regiment. Error bars represent standard deviation, which is dependent on the weight of the subjects.

3.3 Discussion

Using a set of 100 "recruits," we demonstrate the feasibility of a model capable of predicting stress fracture rates, performance enhancement, and metabolic cost simultaneously. Stress fractures were based on a damage progression model (Martin 2001) where we acknowledge the uncertainty in a biological system by using statistical distributions for individual differences, risk factors, fitness level, and fatigue state. The performance component is based primarily on the Banister models (Busso 2003), which utilizes a two component system where enhancement is offset by fatigue. Modifications include performance and skill limiting terms to reflect the difficulty in increasing performance as ability rises. For metabolic cost, the more universal Force Generation algorithm (Sih and Stuhmiller 2003) was used for running and the equation developed by Pandolf et al. (1977) was used for marching. As more data becomes available, we hope to use the Force Generation model to incorporate additional exercises and movements.

As shown in a previous report (Sih et al. 2003), using reasonable parameter values, a model is capable of predicting a stress fracture rate that is in agreement with the observed number of stress fractures. Note that the TOP model gives a daily damage level, which may allow us to identify the ideal time to increase or decrease training to reduce injuries (Figure 9).

The use of a cumulative density function plot gives some important insight into how a population's performance increases with training. Using the parameter values given in Table 12, the performance component of the TOP model was able to reasonably reproduce the test population's both initial and final performance measures (Figure 11). As expected, low initial performers remained slower than their faster counterparts throughout the training regiment. However, their overall gain was larger than more fit individuals. This trend would not be observable from the typical average and standard deviation measures usually reported for a population.

A primary advantage of the TOP model is that both injury and performance are calculated simultaneously, allowing these measured to be plotted together. Using plots like Figure 13, it is possible to see how different individuals respond to training, suggesting changes to the regiment to reduce injury and maximize performance. For example, referring to Figure 13, suppose injury occurs when damage is greater than 0.04 and the objective of training is for 95% of the recruits to have a performance score greater than 0.5 while minimizing injury. A reasonable approach is to reduce training during the final stages of the regiment, reducing injury those recruits who are just over the minimum performance score.

In summary, the TOP model shows trends that are in agreement with that published in the literature but there is significant room for improvement. The model correctly predicts that those with high risk, such as poor initial fitness, accumulate damage rapidly and are more likely to fracture. In addition, as expected the model predicts high performance individuals will continue to perform better but has smaller gains than their untrained counterparts. Unfortunately, we lack high quality data to validate/calibrate the TOP model and our results can only be for demonstration purposes at this time.

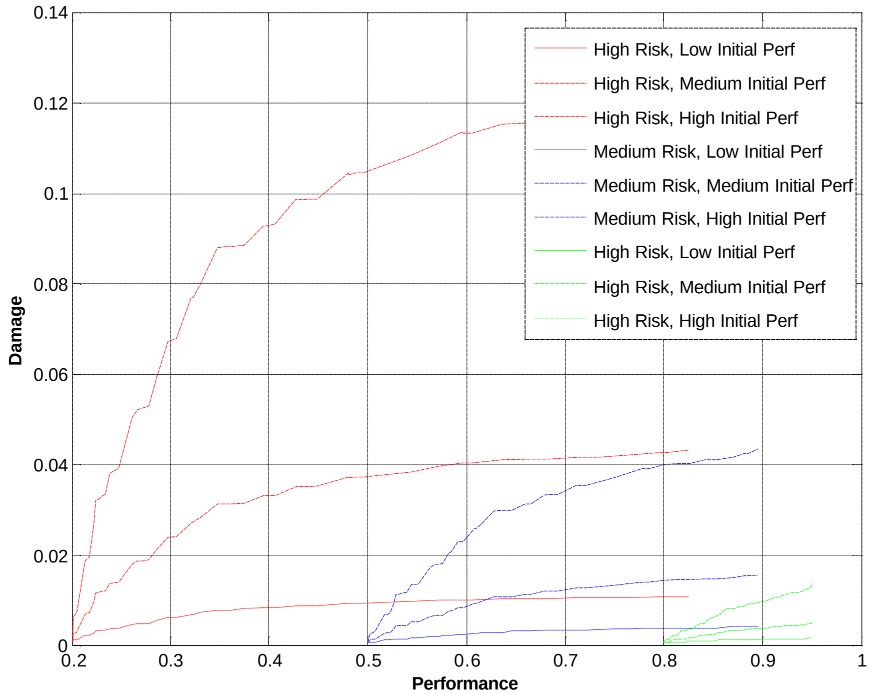

Figure 13. Cross-plot of damage versus performance, which illustrates how different recruits may respond differently to training.

4. Software Conceptual Design

An important aspect of the TOP model is its implementation as a software package, allowing distribution of the model to different users quickly and easily. One of the key features that determine the usability of the program would be the graphical user interface (GUI). In this section, we describe a preliminary GUI design. While the TOP model components are required for the program, these would be inaccessible to the user, who would only be concerned with the input data and output results (see Figure 2).

In order for the TOP model to complete an analysis, there are several general steps that must be accomplished. In a manner similar to a web-based purchase screen, we envision the program guiding users through the different steps while clearly showing the status of each step on the top of the screen (e.g., Figure 15). First, the different TOP model components must be selected (stress fracture, performance, and / or metabolic cost) depending on what question the user is trying to answer. Second, the types of analyses, including cross-analysis between components, are specified (Figure 16). This allows the user to tailor the outputs to only those of interest, reducing output data and computation time. Third, the training regiment is entered. Because of level of complexity can be large, preexisting datasets are available and can be modified, allowing users to more easily enter unique training regiments by changing existing ones. Fourth, key subject information, including anthropometry and health measures, are input. Like the training regiment, the amount of data can be large and complex so preexisting sets are available. In addition, complementary programs can be written to create subject datasets by reading data from military health databases, etc. Global risk factor parameters are also included as part of the subject input (Figure 18). Fifth, after running the simulation, users can view the model's predictions, both in summary and detailed view (Figure 19).

Clearly there are numerous subject and regiment parameters available for modification, making the setup of the program difficult and confusing. A primary goal of the GUI is to make easy to access the more complex parameters easily while not confusing novice users. To address this, in initial data entry screens only general values and pre-existing datasets are shown. However, links to more detailed parameter setup screens are easily accessed from these initial screens (see Figure 18 for an example).

Figure 14. The TOP model will allow users to predict injury, performance, and energy costs associated with a training regiment.

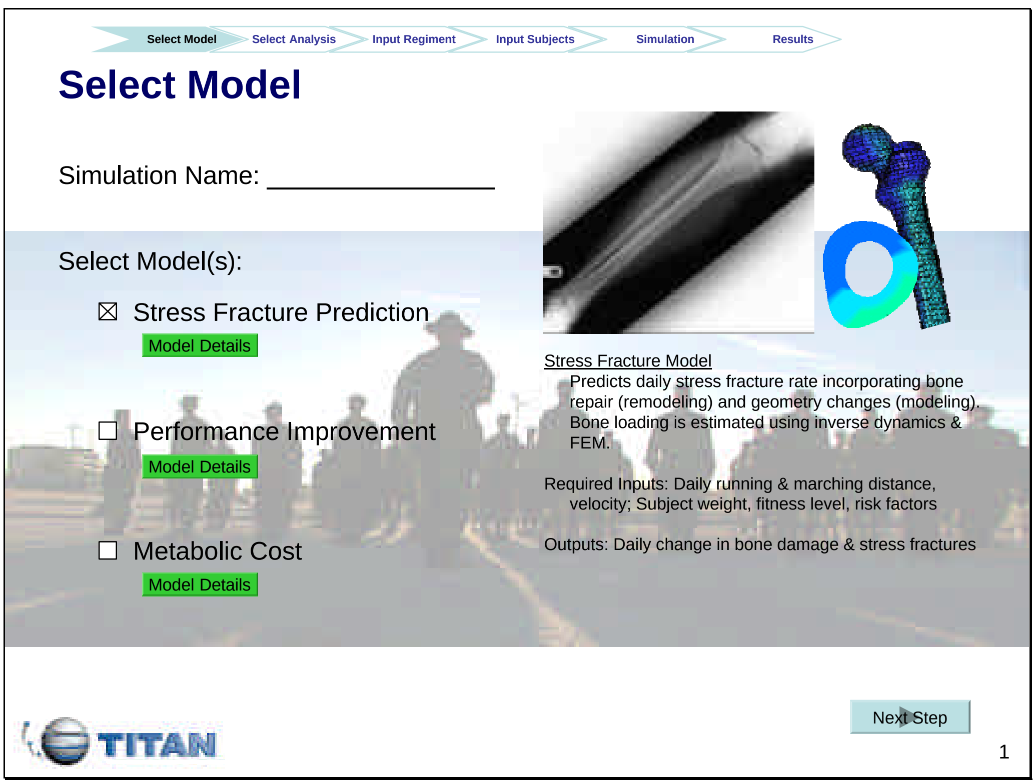

Figure 15. In 'Select Model,' any combination of models can be selected. General details about each model can also be accessed.

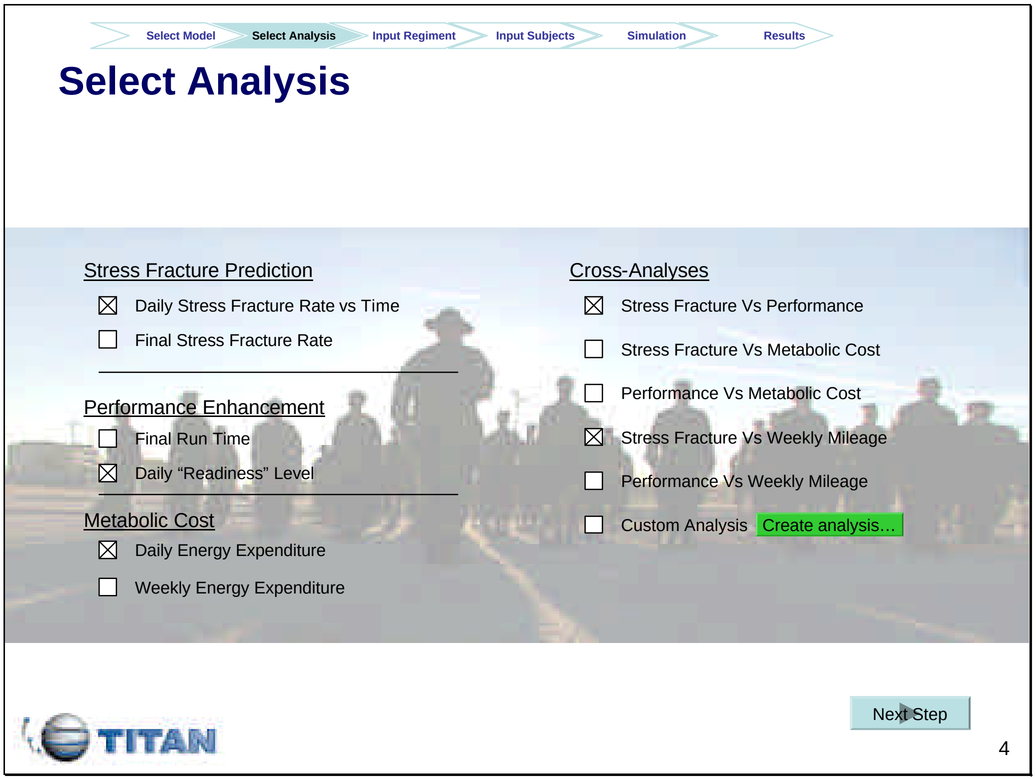

Figure 16. In 'Select Analysis,' the types of outputs are selected, including cross-analyses, which allow results from the different TOP model components to be combined.

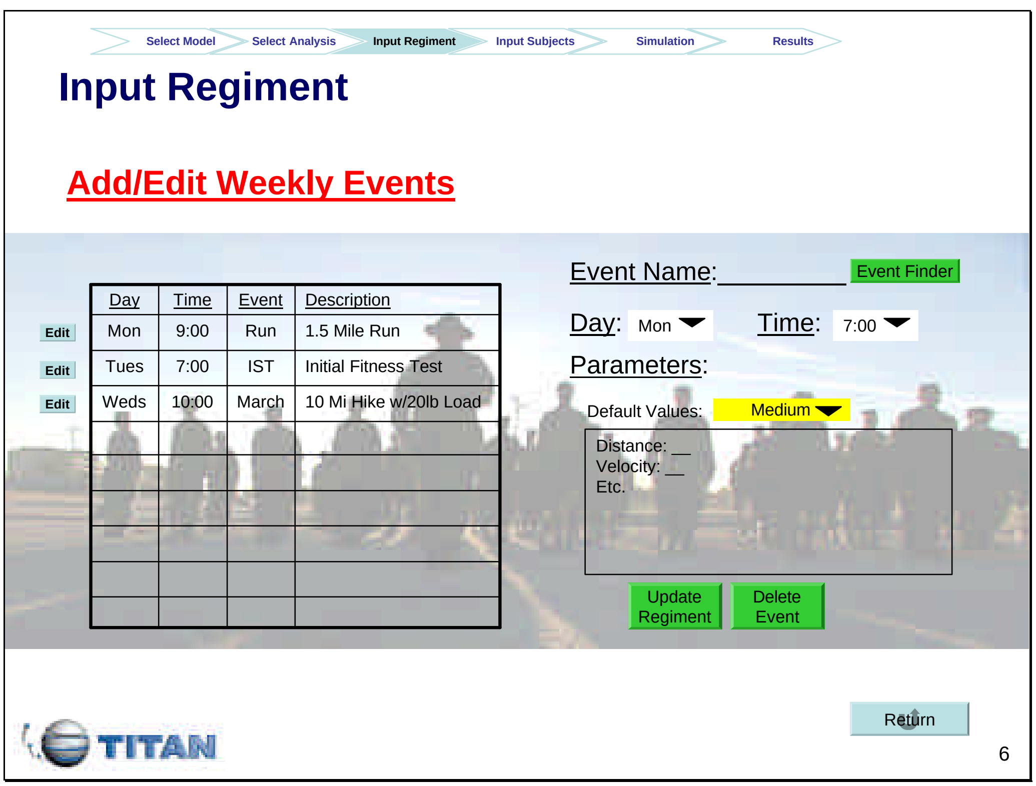

Figure 17. Training regiment details can be entered directly or read in from pre-existing files (not shown).

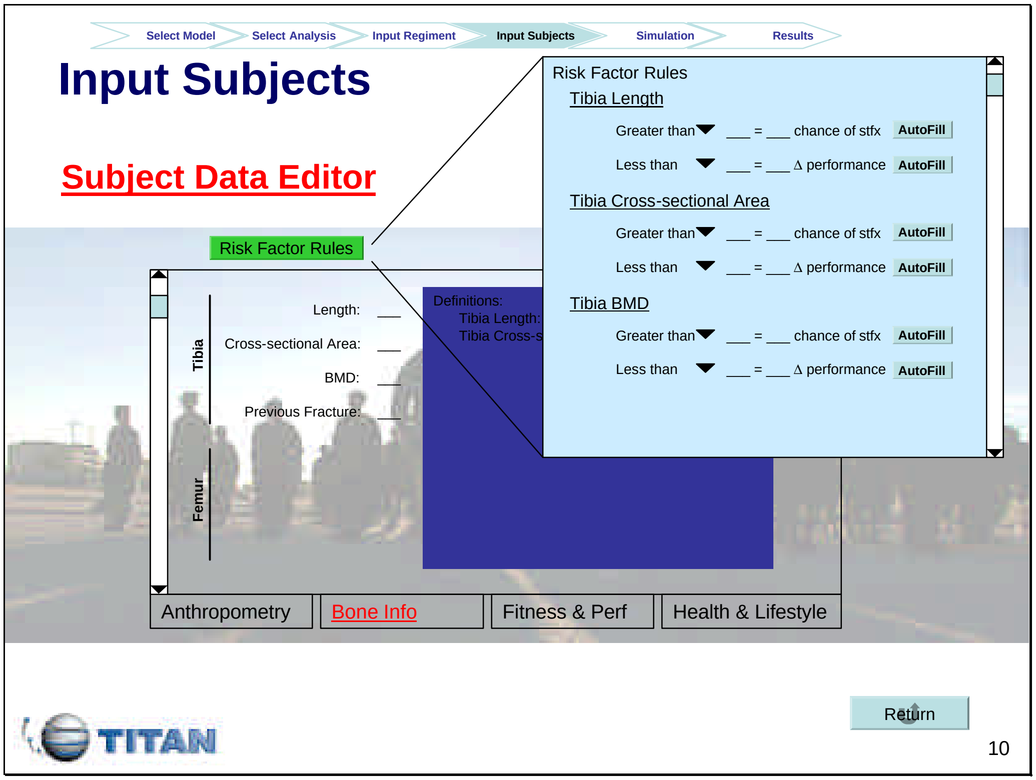

Figure 18. Subject data and risk factor parameters are available for editing or viewing in a simplified tabbed-window system.

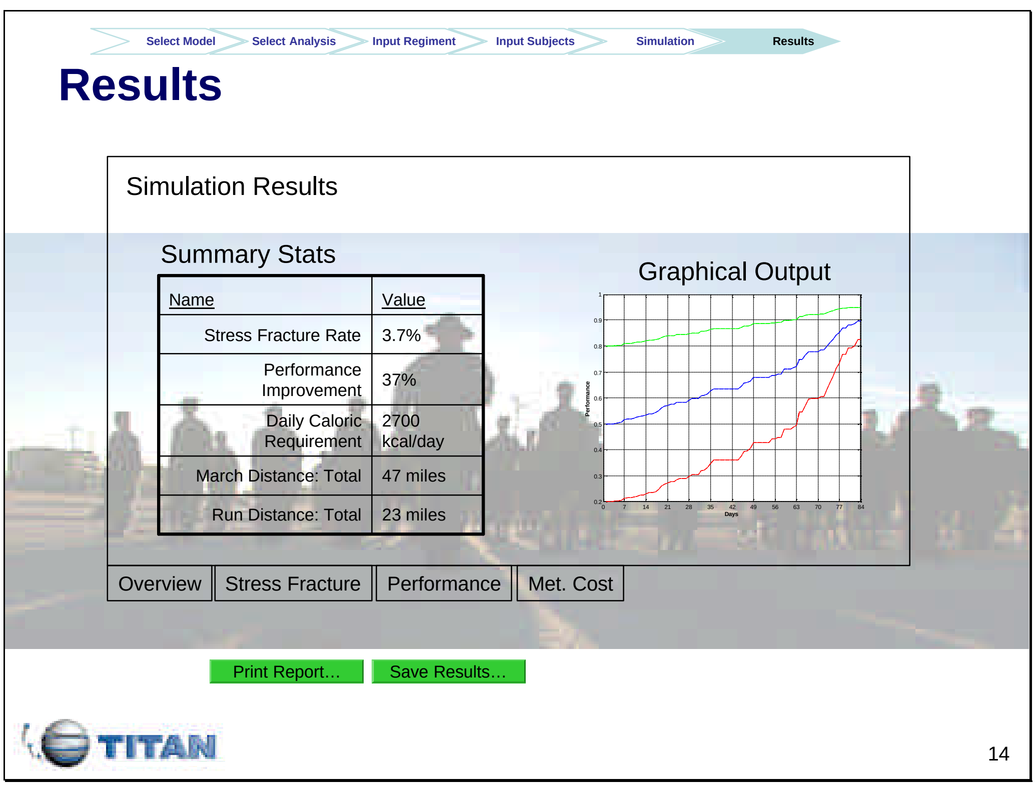

Figure 19. After the TOP model simulation is run, results are displayed. An overview tab allows researchers an easily view the main conclusions and the additional tabs show more detailed results.

5. Training Quantification

Our initial efforts at training quantification focused on marching and running. This section summarizes our effort to expand training quantification to other exercises. Obviously there are several different exercises used in training and the large number of muscles and possible movements makes quantification difficult. Thus, the purpose of training quantification is not only to document the exercises involved, but to develop a method to reduce training to a series of less complex movement categories and muscle groups. In addition, each exercise needs to have a basic set of parameters such as time and pace identified so that biomechanically relevant variables can be estimated through laboratory-derived regressions without the need to monitor exercises in the field. This document identifies the main parameters of each exercise.

In order to reduce the number of possible muscle combinations involved with a movement, we identify seven major muscle groups that are commonly used in training exercise and document the movements they are most responsible for. In addition, training manuals were acquired (see Table 13) and twelve basic movements were identified that are used in different combinations to perform the various training exercises. Thus, a large number of military exercises can be described by a smaller number of simplified movements and muscle groups. By thoroughly studying the simplified movements, it should be possible to reconstruct the military exercises without the need of a full biomechanical analysis of each exercise. See Figure 20.

While this document attempts to be as complete as possible, each training site has the freedom to incorporate their own exercises and drills. Also, this document does not contain information about major field exercises such as the Marine Corp “Crucible,” which may affect both injury rates and performance enhancement.

Note that a thorough biomechanical analysis of the various movements identified in this document is beyond capabilities of our laboratory and collaborations with other, more equipped institutes will be needed. It should also be noted that motivation is probably a dominant factor in both injury and performance, especially with new recruits. Questionnaires may be the best method of quantifying motivation.

Table 13. U.S. Military Training Manuals used to identify training exercises.

Branch	Report Title	Report Number	Full Reference
DoD	DoD Physical Fitness and Body Fat Program	DODD 1308.1	Department of Defense (1995). "DoD Physical Fitness and Body Fat Program." Department of Defense,Report # DODD 1308.1.
DoD	DoD Physical Fitness and Body Fat Programs Procedures	DODI 1308.3	Department of Defense (2002). "DoD Physical Fitness and Body Fat Programs Procedures." Department of Defense,Report # DODI 1308.3.
Army	Physical Fitness Training	FM 21-20 C1	Headquarters Department of the Army (1998). "Physical Fitness Training." Department of the Army, Washington, D.C. Report # FM 21-20 C1.
Army	Enlisted Initial Entry Training (IET) Policies and Administration	TRADOC Regulation 350-6	Headquarters Department of the Army (2001). "Enlisted Initial Entry Training (IET) Policies and Administration." Training and Doctrine Command, Fort Monroe, VA. Report # TRADOC Regulation 350-6.
Marine	Marine Corps Physical Fitness Test and Body Composition Program Manual (MCPFTBCPM)	MCO P6100.12	Headquarters United States Marine Corps (2002). "Marine Corps Physical Fitness Test and Body Composition Program Manual (MCPFTBCPM)." Department of the Navy, Washington, D.C. Report # MCO P6100.12.
Marine	Marine Physical Readiness Training for Combat	FMFRP 0-1B	Marine Corps Combat Development Command (1988). "Marine Physical Readiness Training for Combat." United States Marine Corps, Quantico, VA. Report # FMFRP 0-1B.
Navy	Physical Readiness Program	OPNAVINST 6110.1G	Office of the Chief of Naval Operations (2002). "Physical Readiness Program." Department of the Navy, Washington, D.C. Report # OPNAVINST 6110.1G.
Air Force	The Air Force Fitness Program	AFI 40-501	Air Force Medical Command (2002). "The Air Force Fitness Program." United States Air Force,Report # AFI 40-501.

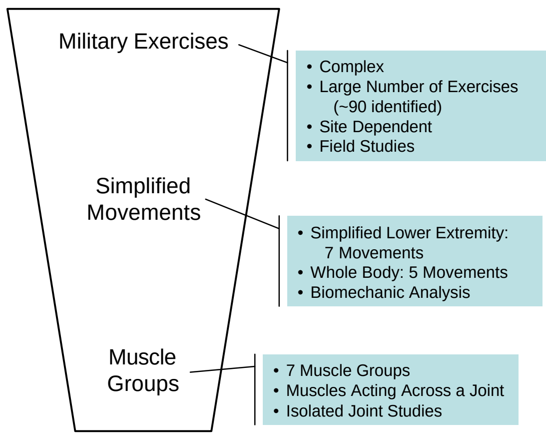

Figure 20. Using movement simplification and muscle groups allows a large number of exercises to be described without the need of a complex muscle-level biomechanical analysis of each exercise.

5.1 Muscle Groups

Performance, fatigue, and even bone strain are affected by the loads generated by muscles. However, incorporating muscle activity into TOP model components is difficult because of the complexity of muscle. Numerous muscles perform the same function, requiring optimization schemes to estimate the load sharing muscles. Also, muscles can perform multiple functions, especially those that cross two joints (biarticulate). Table 14 lists the major muscles of the body and their function, which can be found in most biomechanics text books such as Hall (1995).

To reduce the complexity for the TOP model, Table 15 lists the seven likely muscle groups for most military exercises and the fourteen movements they cause. The focus of these groups is sagittal plane movements, which dominate most exercises. Although major off-plane movements such as adduction of the thigh are ignored in this simplification, it is important to note that large medial-lateral forces may increase bone strains. In the future, zig-zag movements should be documented separately as well as other sideways movements. Forearm movements are also simplified where only flexion of the fingers and forearm are monitored since they are used to grasp.

To properly characterize muscle, geometry measures (cross-sectional area and fiber length), muscle composition (fiber types and motor unit size), and activation (EMG signal, fatigue state, etc.) will have to be further researched.

Table 14. Major movements of the body and the primary muscles. Hall (1995)

Shoulder Complex	
Flexion	Clavicular pectoralis major, anterior deltoid, coracobrachialis
Extension	Sternal pectoralis major, latissimusl dorsi, teres major
Abduction	Middle deltoid, supraspinatus
Adduction	Sternal pectoralis major, latissimusl dorsi, teres major
Horizontal Adduction	Sternal pectoralis major, anterior deltoid, coracobrachialis
Horizontal Abduction	Middle and posterior deltoid, infraspinatus, teres minor
Elbow	
Flexion	Brachialis, biceps brachii, brachioradialis
Extension	Triceps brachi, anconeus
Pronation	Pronator quadratus
Supination	Supinator
Fingers (Forearm)	
Flexion	Flexor digitorum profundus, flexor digitorum superficialis
Hip (Pelvis)	
Flexion	Iliopsoas complex, rectus femoris, tensor fasciae latae, sartorius, pectineus
Extension	Semitendinosus, semimembranosus, biceps femoris, gluteal muscles
Adduction	Adductor magnus, adductor longus, adductor brevis, gracilis
Knee	
Flexion	Semitendinosus, semimembranosus, biceps femoris
Extension	Quadriceps muscles
Ankle	
Dorsiflexion	Tibialis anterior, extensor digitorum longus, peroneus tertius, extensor hallucis longus
Plantar flexion	Gastrocnemius, soleus, tibialis posterior, peroneous muscles, Foot flexor muscles
Spine	
Flexion	Rectus abdominis, oblique muscles
Extension	Erector spinae group

Table 15. Recommended simplified movement categories to quantify military training exercises.

Shoulder Complex	
Deltoids	Anterior, posterior, middle
Adduction	Sternal pectoralis major, latissimusl dorsi, teres major, coracobrachialis
Abduction	Supraspinatus, deltoids
Elbow	
Flexion	Brachialis, biceps brachii, brachioradialis
Extension	Triceps brachi, anconeus
Forearm	
Flexion	Flexor digitorum profundus, flexor digitorum superficialis
Hip	
Flexion	Iliopsoas complex, rectus femoris, tensor fasciae latae, sartorius, pectineus, adductor magnus, adductor longus, adductor brevis, gracilis
Extension	Semitendinosus, semimembranosus, biceps femoris, gluteal muscles
Knee	
Flexion	Semitendinosus, semimembranosus, biceps femoris
Extension	Quadriceps muscles
Ankle	
Dorsiflexion	Tibialis anterior, extensor digitorum longus, peroneus tertius, extensor hallucis longus
Plantar flexion	Gastrocnemius, soleus, tibialis posterior, peroneous muscles, Foot flexor muscles
Spine	
Flexion	Rectus abdominis, oblique muscles
Extension	Erector spinae group

5.2 Movement Simplification

While marching and running are the most common whole-body movements, obstacle negotiation is an important part of military training. Obstacles are unique in that a wide variety of structures are used and each recruit is free to negotiate the obstacle in almost any manner. Unfortunately, this makes quantification difficult.

A review of the exercises described in the training manuals (see Table 13) suggests that many of the exercises can be described using a set of simpler movements. This section describes a set of movements that we believe can be combined to describe the majority of the more complex training exercises. Movements are broken down into two general categories: lower extremity and whole body. Because even simplified movements will require a thorough biomechanical analysis to determine muscle and bone forces, our initial efforts will be on the lower extremity, where the largest muscles dominant the movements. In addition, for each of the simplified movements, a more detailed literature review is needed to determine what biomechanical information is already available.

5.2.1 Simplified Lower Extremity Movements

The following movements involve the lower extremity such as running and marching. Because landing can be done without jumping (i.e., off a platform), we treat jumping as the take-off portion and landing as a separate event. These movements are important because they involve the largest muscles in the body, bear the brunt of impact forces, and must withstand large forces. Table 16 indicates the muscle groups likely involved. A literature review and/or biomechanical analysis will be needed to verify these muscle groups and determine their relative contribution to the movement. We follow with a brief description of each movement, including the likely parameters needed for quantification Table 17.

Table 16. Summary table of the muscle groups likely involved in the primary movements of the lower extremity.

	Movement Categories													
Main Lower Body	*Shoulder Complex*			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*	
Movements	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.
Running	x			x			x	x	x	x		x		x
Marching							x	x	x	x		x		x
Hopping								x		x		x		
Jumping	x		x					x		x		x		x
Landing	x							x		x		x		x
Heavy Steps										x				x
Zig-Zags								x		x		x		x

Table 17. Summary table of likely parameters needed to describe the primary lower extremity movements.

Running	Marching	Hopping	Jumping	Landing	Heavy Steps	Zig-Zags
Stride Rate	Stride Rate	Hop Rate	Approach (e.g. stand, run)	Height		Incoming and Outgoing Velocity
Stride Length	Stride Length		Jump Height	Landing Style (one or two legs)		Direction Change Angle
Velocity	Velocity		Horizontal Velocity	Horizontal Velocity		
	External Load					

Running

Easily the most common higher intensity exercise, running will need to be fully quantified from a biomechanical point of view. Fortunately, the movement has been analyzed in detail with numerous reports in the literature.

Basic Parameters : Stride Rate; Stride Length; Velocity

Marching

Marching is probably closely related to walking but often done in military boots. There are conflicting reports but some studies suggest boots may significantly affect the loading conditions on the body (Finestone et al. 1992; Williams et al. 1997). Although weight is only carried during marches, the additional load will also affect the loading conditions. A detailed literature review on this topic will need to be done, but it is likely that there is enough information in the literature that a new study will not be needed.

Basic Parameters: Stride Rate; Stride Length; Velocity; External Load

Hopping

There are many instances where hopping, rather than a maximal jump, is required in both exercise drills and obstacle courses. Although unverified, it is likely that hopping is dominated by the calf muscles and plantar flexion. This movement may be a source of tibial bone strains. Also, in general, more hops than jumps are performed by recruits.

Basic Parameter: Hop Rate

Jumping

For the purposes of quantifying training regiments, jumping is primarily defined as a maximal or near-maximal take-off where the arms are swung to increase height. Landing is covered as a separate movement. There should be multiple studies involving jumping in the literature.

Basic Parameters: Approach (standing, running); Jump Height; Horizontal Velocity

Landing

Landing is covered separately from jumping since courses can have ditches and other obstacles that require a landing without performing a jump first. Note that velocity at impact is dependent on height and follows simple projectile motion equations.

Basic Parameters: Height; Landing Style (one or two legs); Horizontal Velocity

"Heavy Steps"

Another common movement is stepping over low obstacles or taking larger than normal steps to navigate logs, etc. The ground reaction forces required for this type of movement is likely larger than normal but the parameters that describe stepping is unknown. A literature review needs to be conducted to investigate this movement and quantify changes in ground reaction forces.

Basic Parameters: Unknown

Zig-Zags

Zig-zags involve quickly changing direction while running and require additional balance, coordination, and muscle forces compared to running forward. The lateral forces may also increase bone strains of the tibia and femur since these bones are may not be designed to minimize strains from this direction.

Basic Parameters: Incoming and Outgoing Velocity; Direction Change Angle

5.2.2 Major Whole-Body Movements

Whole-body movements are important because of the decreased time to fatigue that result from using a large number of muscles. In addition, these movements require the coordination of the smaller upper body muscles, which may lead to neurological fatigue. Thus, the ability of these muscles to generate force will have a significant effect on performance. Table 18 indicates the muscle groups likely involved for the set of whole body movements typically used during basic training. A literature review and / or biomechanical analysis will be needed to verify these muscle groups and determine their relative contribution to each movement. We follow with a brief description of the movements, including the likely parameters needed for quantification (Table 19).

Table 18. Summary table of the muscle groups likely involved in the primary movements of the whole body.

	Movement Categories													
Main Whole Body Movements	*Shoulder Complex*			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*	
	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.
Ladder Climbing		x			x	x		x		x		x		
Cargo Net Climbing		x			x	x		x		x		x	x	x
"Climb-Overs"		x		x		x	x					x	x	
Crawling	x	x		x			x	x	x	x			x	x
Arm Swinging	x	x		x		x							x	

Table 19. Summary table of likely parameters needed to describe the primary movements of the whole body.

Ladder Climbing	Cargo Net Climbing	"Climb-Overs"	Crawling	Arm Swinging
Length Traveled	Length Traveled	Height of obstacle	Distance	Distance or Time
Angle of Net	Angle of Ladder	Climbing Technique	Mode of Crawling	
# of Rungs	# of Rungs	Dismounting Technique	Velocity	

Cargo Net Climbing

The ability to climb cargo nets is probably more demanding than climbing a fixed structure such as a ladder. A literature review may reveal more details but it is likely to entail greater upper body and trunk strength.

Basic Parameters: Length Traveled; Angle of Net; # of Rungs

Ladder Climbing

Ladder climbing is probably dominated by the leg muscles as arms are used primarily to center the body over the legs. A literature review is needed to confirm this.

Basic Parameters: Length Traveled; Angle of Ladder; # of Rungs

"Climb-Overs"

A common movement for the obstacle course is dealing with obstacles that are too high to jump over and must be navigated by climbing and swinging the legs over. Thus, upper body strength is needed to grasp the top of the obstacle and trunk strength is needed to lift the legs over. A literature review is needed but this movement is likely fatiguing since the obstacles are often unwieldy and the muscles used to grasp may not be fully developed (i.e., shoulders, chest, forearms).

Basic Parameters: Height of obstacle; Climbing Technique; Dismounting Technique;

Crawling

There are several "modes" of crawling such as over logs (e.g., Belly Robber), under low obstacles, or on the back. The physical demands of these movements may be different and might need to be categorized separately.

Basic Parameters: Distance; Mode of Crawling; Velocity

Arm Swinging

Soldier must have strong forearm strength and endurance to support body weight.

Basic Parameters: Distance or Time;

5.3 Exercises

5.3.1 Running Exercises

In addition to the standard 1-3 mile run prescribed during basic training, there are several running variations designed to keep individuals motivated. These exercises involve grouping individuals with similar ability as well as incorporating sprints and formation drills. Ultimately, the loading conditions dealt to the body and the muscle forces generated while running (and any other exercise) depend on an individual's anthropometry and fitness level. However, there are several additional parameters that describe these different acts of running. Note that most military runs are supposed to be in running shoes with no load. See Table 20.

Table 20. Different running exercises used in military training and likely parameters needed to quantify the training. Running exercise definitions can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998).

Ability	Interval	Fartlek	Last-Man-Up	Cross country
Distance or Pace	Time & Distance or Pace for Effort	Time & Distance or Pace for Effort	# Soldiers	Distance or Pace
Time	Time & Distance or Pace for Rest	Time & Distance or Pace for Rest	Group's Pace	Time
Footwear	Activity During Rest Interval	Number of Efforts	Total Time	Footwear
Load	Number of Intervals		Average Time to Complete Sprint	Load
Terrain				Terrain

5.3.2 Marching & Hiking

Marches for exercise (as opposed to marching in formation) are usually 5 km or greater, performed while carrying load, and are referred to as road marches. For Initial Entry Training (IET), road marching distances should progress gradually. The U.S. Army's recommended sample road march is given in their Physical Fitness Training Manual FM 21-20 (Headquarters Department of the Army 1998). Speed for a road march is approximately 4.8 km/hr. If a 10 minute rest is taken each hour, a speed of 4 km/hr can be expected. Footwear is usually boots. Unless specified, assume most training marches are administrative (not tactical, which requires lookouts, etc.).

Basic Parameters: Distance or Pace; Time; Load; Footwear; Terrain

5.3.3 Obstacle & Conditioning Courses

The U.S. Army and U.S. Marine Corps Confidence Courses are similar, being based on the same U.S. Army Corps of Engineers design (DEF 028-13-95). The typical Confidence Course is composed of four quadrants, each of which contains approximately 6 obstacles to navigate. There is a central assembly area where each quadrant can be accessed. See Figure 21. Obstacles are generally 20 to 30 yards apart.

Both the Army and Marine Corps Confidence Courses are not timed and are often done in small groups (4-8 soldiers). Some obstacles require teamwork to navigate and completion of a confidence course is not considered as a measure or a requirement for physical fitness.

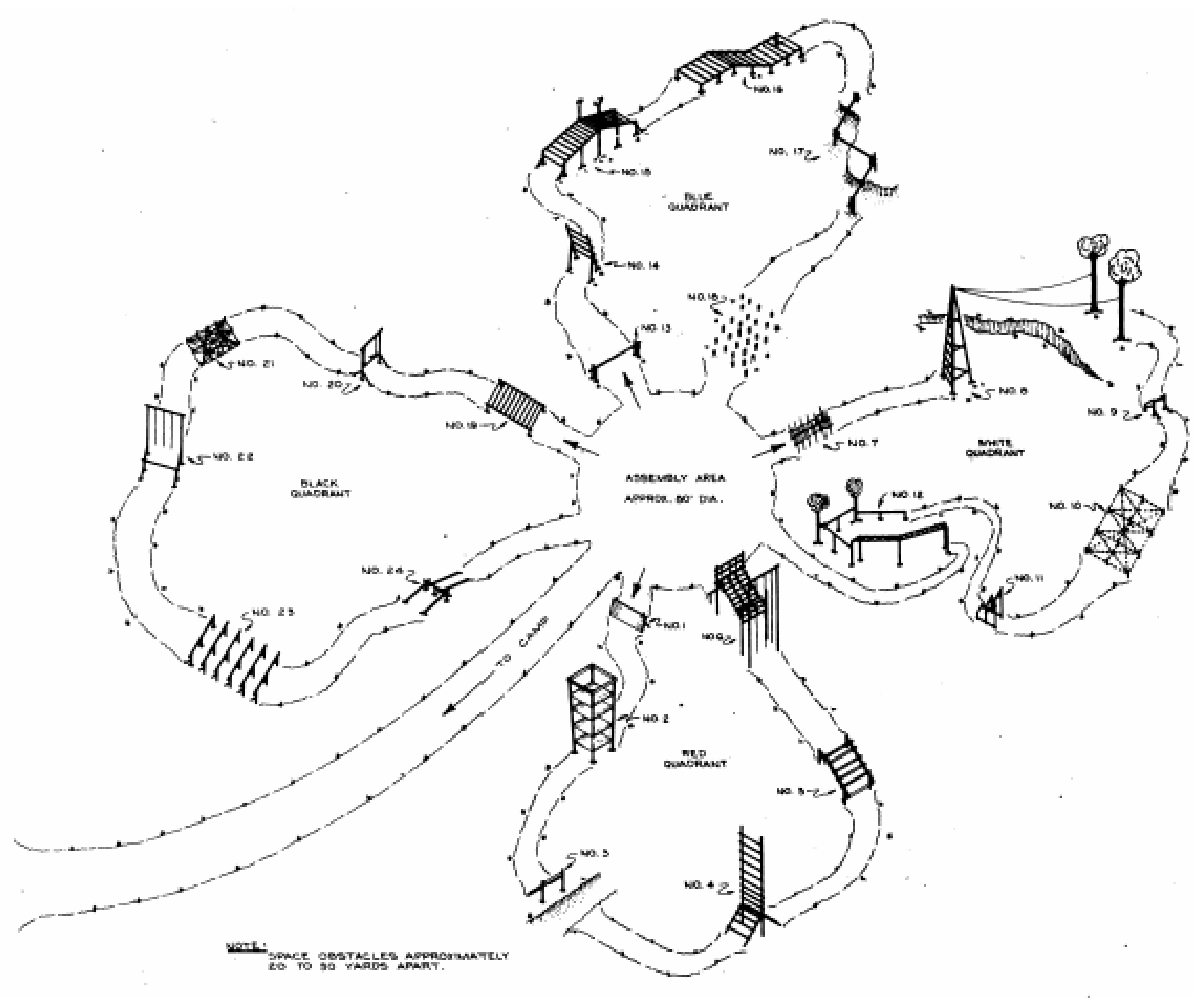

Figure 21. Confidence Course Layout Plan. From Sheet 1 of DEF 028-13-95. (U.S.Army Corps of Engineers 1952)

The primary requirements for the obstacle course are probably upper body strength and leg lifting, which are needed for the large amount of climbing and crawling. Coordination and balance are also important.

By design (and recent course modifications), the number of high loading impacts due to landing and jumping have been reduced. However, there are several hurdle-type obstacles that may elevate bone strains. Although most obstacles are designed to prevent injury, falls from obstacles can also cause elevated bone strains.

Detailed quantification of a confidence course will be difficult because each recruit may navigate an obstacle using a different method, and because the course is not timed, effort levels may vary widely. In addition, landing impact is dependent on initial height and velocity but may be difficult to determine. For example, a recruit sliding off a log face-forward will have a higher impact than a recruit who turns around and hangs on to the log to slowly drop to the ground. Nevertheless, it should be possible to estimate typical loading patterns. A breakdown of the simplified lower extremity and major whole body movements needed to complete each obstacle can be found in Table 21.

Table 21. Obstacle course stations with the simplified lower extremity and major whole body movements required to complete. Obstacle details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998).

	Run	Hop	Jump	Land	Heavy Steps	Ladder Climb	Cargo Net Climb	"Climb-Overs"	Crawl	Arm Swing
Between Obstacles	x									
The Tough One						x	x			
Inverted Rope Decent						x				x
Confidence Climb						x		x		
Skyscaper								x		
Belly Robber									x	
The Tarzan										x
Low Belly Over			x	x				x		
The Dirty Name			x					x		
The Tough Nut					x					
Belly Crawl									x	
Inclining Wall			x	x				x		
Hight Step Over					x					
Swing, Stop & Jump	x			x						x
Six Vaults			x	x				x		
Easy Balancer										
Low Wire									x	
The Belly Buster			x	x				x		
Hip-Hip					x					
Reverse Climb						x		x		
The Weaver								x		
Balancing Logs		x								
Island Hoppers										

The conditioning course has low obstacles that must be negotiated quickly. Running the course can be a test of the soldier's basic motor skills and physical condition. After soldiers receive instruction and practice the skills, they run the course against time. (Headquarters Department of the Army 1998)

The guidelines for creating a conditioning obstacle course are not strict and each obstacle course may be different. However, there are general guidelines. If possible, an obstacle course should be shaped like a horseshoe or figure eight so that the finish is close to the start. Also, signs should be placed to show the route. A course usually ranges from 300 to 450 yards and has 15 to 25 obstacles that are 20 to 30 yards apart. The obstacles are arranged so that those which exercise the same groups of muscles are separated from one another.

Because conditioning courses are timed (and performed individually, and not as a group), the effort level is presumed to be higher. If the obstacles can be quantified successfully, the course may be a good measure of overall fitness and allow comparison of fitness between recruits using different courses. However, if the time limit is sufficiently long, effort level may drop of markedly in unmotivated recruits.

There are numerous options available for obstacles. Table 22 lists a few common obstacles with the simplified lower extremity and major whole movements that are necessary to complete the obstacle.

Table 22. Some conditioning course obstacles with the simplified lower extremity and major whole body movements required to complete. Obstacle details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998).

Jumping	Zig-Zags	Climbing	Arm Swinging	Crawling	Climb-Overs
Ditch	Lanes	Rope	Pipe	Tunnel	Fence
Trench	Mazes	Cargo Net	Beam	Low Rail	Low Wall
Platform		Wall	Ladder	Wire	
Hurdles		Pole	Rope		

5.3.4 Strength Training Exercises (Circuit Training)

A circuit is a group of stations or areas where specific tasks or exercises are performed. The objective of the circuit plus the time and equipment available strongly influence the number of stations. A circuit geared for a limited objective (for example, developing lower-body strength) needs as few as six to eight stations. On the other hand, circuits to develop both strength and CR fitness may have as many as 20 stations. The U.S. Army Physical Fitness Training document FM 21-20 (Headquarters Department of the Army 1998), describes the circuits used by the Army. The Marines training document is FMFRP 0-1B (Marine Corps Combat Development Command 1988).

In general, there are two types of circuits: free and fixed. In a free circuit, there is no set time for each station and no signal is given to move to the next station. In a fixed circuit, a specific length of time is set for each station. Note that regulations suggest allowing from 5 to 7 minutes both before and after running a circuit for warming up and cooling down. Table 24 and Table 25 lists the common U.S. Army and Marine strength training exercises, respectively, as well as the simplified movements each exercise requires.

From the tables, it is clear that there are many different exercises using various pieces of equipment, each of which is designed to stress a particular muscle or group of muscles. In Table 23 we list some of the parameters that will be needed to properly quantify a circuit. Quantification of the load will depend highly on the time given, as well as the strength and the motivation of the recruit. In addition, the effectiveness of the exercise (and the ability to model changes in performance) may be highly dependent on the recruit using proper form. Also, the initial status of the muscles (fatigue, strength level, etc.) is likely to play an important role.

Table 23. Possible parameters to describe a strength training circuit.

Type	Free or fixed stations
Time	To complete entire circuit; at eahc station; between stations; warm-up and cool-down
# Stations	
# of Completions	Number of times a circuit is completed
Sequence	Order of stations
Station Exercise	Exercise; number of reps
Exercise Btwn Stations	Running, jumping, etc., including time and/or distance

Table 24. A compilation of the U.S. Army strength training exercises. Most exercises can be performed with a partner (partner-resisted exercises), with free weights, or exercise machines. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998)

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Exercise	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Squat								x		x					
Split-Squat								x		x					
Single-Leg Squat								x		x					
Leg Press								x		x					
Leg Extension										x					
Leg Curl									x						
Bent-Leg Dead-Lift		x				x		x		x				x	
Heel Raise (Bent Over)												x			
Toe Raise											x				
Push-Up			x		x										
Seated Row		x		x											
Bent-Over Row		x		x		x									
Overhead Press	x				x										
Bench Press	x		x		x										
Pull-Down		x													
Shrug		x													
Triceps Extension					x										
Parallel Bar Dip			x		x										
Biceps Curl				x											
Chin-Up		x		x		x									
Wrist Curl						x									
Abdominal Curl													x		
Abdominal Crunch													x		
Sit-Up									x				x		
Incline Sit-Up									x				x		
Back Extension														x	

Table 25. A compilation of U.S. Marine strength training exercises. Exercises listed are from fixed and moveable strength circuits. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998) and Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Exercise	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Pull-Ups/Chin-Ups		x		x		x									
Twist Grip						x									
Pulley Weights		x				x									
Barbell Curls				x		x									
Step-Up								x		x					
Leg Lift						x	x						x		
Rope Climb															Climbing
Bent Knee Sit-Up													x		
Bottoms Up			x							x		x			
Push-Up			x		x										
Knee Bender								x		x		x		x	
Trunk Twister														x	
Barbell-2Hand Mil.Press	x		x		x	x		x		x				x	
Barbell-2Hand Reg.Curl				x		x		x		x				x	
Jump Rope															Hop
Incline Plane													x		
War Club		x	x										x	x	
Bicycle Ride								x					x	x	
Isometric Pull		x		x											

5.3.5 Conditioning Drills

There are many different conditioning drills utilized by the military and are categorized differently depending on military branch. While some exercise drills have a defined regiment and time, most exercise-type drills are less structured than circuit training, making quantification difficult. In general, the parameters need to describe exercise drills is the same as those for circuit strength training.

The following tables list most of the drills used by the U.S. Army and Marine Corps. The muscle groups and movements involved are also given. Note that a detailed literature review or biomechanical analysis is needed to verify the movement categories and determine the typical kinetic and kinematic profiles for these movements.

Table 26. U.S. Army calisthenic exercises. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998)

	Movement Categories														
Calisthenic	*Shoulder Complex*			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Exercises	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Side-Straddle Hop	x											x			Hop, Zig-Zag
Mule Kick							x		x						Hop
Ski Jump												x			Hop, Zig-Zag
Flutter Kick							x			x			x		
Bend and Reach														x	
High Jumper	x							x		x		x		x	Jump, Land
Squat Bender	x							x		x		x		x	
Lunger	x							x		x				x	
Knee Bender								x		x		x		x	
The Swimmer	x							x						x	
Supine Bicycle							x						x		
The Engine	x						x						x		
Cross-country Skier		x	x				x	x		x		x			Hop
Push-Up			x		x										
Sit-Up							x						x		
Chin-Up (Pull-Up)		x		x		x									
Parallel Bar Dip			x		x										

Table 27. U.S. Marine Corps conditioning drills. Exercise details can be found in Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
Conditioning	*Shoulder Complex*			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Drills	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Trunk Twister														x	
Body Twist													x		
Jumping Jack	x							x		x				x	Hop
Turn and Bend	x													x	
8 Count Push-Up			x		x										
Turn and Bounce													x	x	
Squat Stretch															
Leg Circular													x		
Back Bender													x		
Squat Thrust	x							x					x		
Side Bender													x	x	
Bottoms-Up			x							x		x			

Table 28. U.S. Marine Corps Daily 16 conditioning exercises. Exercise details can be found in Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
Daily 16 Conditioning	*Shoulder Complex*			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Exercises	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Push-Ups			x		x										
Crunches													x		
Dirty Dogs								x							
Wide Push-Ups			x		x										
Dive Bomber Push-Ups			x		x										
Elbow-Knee Crunches													x		
Side Crunches													x		
Prone Flutter Kicks								x						x	
Back Extension														x	
Donkey Kicks								x							
Hip Adduction							x								
Side Leg Raises							x								
Steam Engine							x						x		
Lunges								x		x					
Side Straddle Hops	x											x			Hop

Table 29. Grass Drill exercises used by the U.S. Army and Marine Corps. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998) and Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Grass Drills	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Go							x					x			Run
Front to Back			x										x		
Back to Front			x										x		
Bouncing Ball			x		x							x	x		
Supine Bicycle							x						x		
Knee Bender								x		x		x		x	
Roll Left and Right													x	x	
Bound & Clap Hands			x		x							x	x		
Leg Spreader													x		
Forward Roll															
Stationary Run							x					x			Run
Bicycle								x		x					
Sit-Up							x						x		
Full Squatter								x		x		x		x	
Mountain Climber							x	x	x	x		x			
Legs Over													x		
V-Up and Touch Toes													x		
Rocker														x	

Table 30. Guerilla Exercises used by the U.S. Army and Marine Corps. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998) and Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Guerilla Exercises	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
All-Fours Run			x		x					x		x			
Bottoms-Up Walk			x		x							x			
Crab Walk					x			x						x	
The Engine	x						x						x		
Double Time								x				x			Run
Broad Jump								x		x		x		x	Jump, Land
Straddle Run								x		x		x		x	Run, Zig-zag
Hobble Hopping								x		x		x			Hop, Hvy Stps
Fireman's Carry				x	x									x	Hvy Stps
Single-Shoulder Carry				x						x				x	Hvy Stps
Cross Carry				x		x								x	Hvy Stps
Saddle-Back Carry				x				x		x				x	Hvy Stps

Table 31. Additional Guerilla Exercises used by the U.S. Marine Corps. Exercise details can be found in Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
Guerilla	*Shoulder Complex*			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Exercises	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Squat Walk							x			x					
Toe-Touch Walk														x	
Toe-Grasp Walk														x	
Hand-Kick Walk							x								HvyStps
Pike Jumping							x						x		Jump, Land
Squat Jump								x		x		x		x	Jump, Land
Steam Engine							x						x		
Knee-Touch Walk								x		x					

Table 32. U.S. Army and Marine Corps Rifle Drills. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998) and Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Rifle Drills	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Up and Forward	x														
Fore-Up, Squat	x							x		x					
Fore-Up, Behind Back	x														
Fore-Up, Back Bend	x												x		

Table 33. Additional Rifle Drills used by the U.S. Marine Corps. Exercise details can be found in Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Rifle Drills	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Lunge Side,Turn&Bend	x									x				x	
Arms Fwd, Side Bend														x	

Table 34. Log Drill exercises used by the U.S. Army and Marine Corps. Exercise details can be found in Physical Fitness Training FM 21-20 (Headquarters Department of the Army 1998) and Marine Physical Readiness Training for Combat FMFRP 0-1B (Marine Corps Combat Development Command 1988).

	Movement Categories														
	Shoulder Complex			*Elbow*		*Forearm*	*Hip*		*Knee*		*Ankle*		*Spine*		*Gen.Movements*
Log Drills	Delts.	Add.	Abd.	Flex.	Ext.	Flex.	Flex.	Ext.	Flex.	Ext.	D.Flex.	P.Flex.	Flex.	Ext.	
Start to Shoulder			x	x		x		x		x				x	
Start to Waist						x		x		x				x	
Waist to Chest			x	x										x	
Two-Arm Push-Up	x				x										
Forward Bender		x		x		x		x						x	
Straddle Jump								x		x					
Side Bender								x		x					
Half Knee Bend								x		x					
Overhead Toss	x				x			x		x		x			

6. Conclusion

This report documents the progress made towards combining our previous work in injury modeling with a new performance prediction algorithm. With further enhancements, this combination should allow the military to better design training regiments by optimizing performance while reducing injury, a primary objective of basic training. The framework laid out in this document will also give guidance on the importance of existing research and areas lacking in knowledge, which is needed to further improve the TOP model in an efficient manner. In addition, all components of the TOP model require an accurate quantification of training and substantial steps have been made to document and quantify the movements and muscle groups used in most the exercises used during basic training.

Future work includes broadening the model framework to include addition ongoing research, validation of various model components by biomechanical testing and analysis, and implementation of the application software.

Key Research Accomplishments:

- Framework for both injury and performance
- Implementation of a performance, injury, and metabolic cost models
- Software conceptual design
- Basic quantification of most training exercises

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